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TITLE: **The Influence of Olfaction on the Perception of High-Fidelity Computer Graphics**

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The Influence of Olfaction on the Perception of High-Fidelity Computer Graphics

by

Belma Ramić-Brkić

Thesis

Submitted to the University of Warwick

for the degree of

Doctor of Philosophy

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In loving memory of my uncle

Mirsad Čaušević.

Declaration

I, Belma Ramić-Brkić, hereby declare that the work presented in this thesis is original and no portion of the work referred to here has been submitted for the award of any other degree or diploma of the university or other institute of higher learning, unless otherwise stated by referencing.

Signature: Belma R. Brkić
Belma Ramić-Brkić

Date: 17 December 2012

List of Publications

The following have been published as a result of the work contained within this thesis.

Journal papers

- A. Chalmers, K. Debattista and B. Ramić-Brkić. Towards high-fidelity multi-sensory virtual environments. The Visual Computer, Volume 25, Number 12, pp 1101-1108, 2010.

Conference papers

- B. Ramić-Brkić, A. Chalmers, A. Sadzak, K. Debattista and S. Sultanić. Exploring multiple modalities for selective rendering of virtual environments. In SCCG '13: Proceedings of the Spring Conference on Computer Graphics. ACM SIGGRAPH, 2013.

- B. Ramić-Brkić and A. Chalmers. Virtual smell: Authentic smell diffusion in virtual environments. In Proceedings of the 7th International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa, Franschhoek, South Africa, June 21-23, 2010.

- B. Ramić-Brkić, A. Chalmers, K. Boulanger, S. Pattanaik and J. Covington. Cross-modal effects of smell on the real-time rendering of grass. In SCCG '09: Proceedings of the Spring Conference on Computer Graphics. ACM SIGGRAPH, 2009.

- B. Ramić, A. Chalmers, J. Hasić and S. Rizvić. Selective Rendering in a Multimodal Environment: Scent and Graphics. In SCCG '07: Proceedings of the Spring Conference on Computer Graphics. ACM SIGGRAPH, 2007.

Abstract

The computer graphics industry is constantly demanding more realistic images and animations. However, producing such high quality scenes can take a long time, even days, if rendering on a single PC. One of the approaches that can be used to speed up rendering times is Visual Perception, which exploits the limitations of the Human Visual System, since the viewers of the results will be humans. Although there is an increasing body of research into how haptics and sound may affect a viewer's perception in a virtual environment, the influence of smell has been largely ignored. The aim of this thesis is to address this gap and make smell an integral part of multi-modal virtual environments.

In this work, we have performed four major experiments, with a total of 840 participants. In the experiments we used still images and animations, related and unrelated smells and finally, a multi-modal environment was considered with smell, sound and temperature. Beside this, we also investigated how long it takes for an average person to adapt to smell and what affect there may be when performing a task in the presence of a smell.

The results of this thesis clearly show that a smell present in the environment firstly affects the perception of object quality within a rendered image, and secondly, enables parts of the scene or the whole animation to be selectively rendered in high quality while the rest can be rendered in a lower quality without the viewer noticing the drop in quality. Such selective rendering in the presence of smell results in significant computational performance gains without any loss in the quality of the image or animations perceived by a viewer.

Chapter 1

Introduction

1.1 Motivation

Despite the huge progress in the performance of graphics-related hardware in recent years, rendering of high-fidelity images and animations can take a long time. In an attempt to achieve such high-fidelity images in a reasonable time, special techniques may be applied, which employ perceptually based criteria to speed up the computation of the rendering by focusing only on those image features that are readily perceivable under certain viewing conditions [32, 131]. Research has shown how images can be rendered selectively, with the parts a user is attending to rendered in high quality, and the rest in a much lower quality (and thus at a reduced computational cost), without a noticeable perceptual difference to the user. The visual perception thus represents a growing area of importance for research in computer graphics and is increasingly being exploited to improve the quality of displayed images and to reduce the time needed to render them.

Despite the significant research into the limitation of the Human Visual System within Computer Graphics and its exploitation in new rendering algorithms, little work has been undertaken into the strong cross-modal interactions between visual and other sensory stimuli. The real world contains physically related multi-modal features. Several psychological surveys have shown that stimuli reaching the various senses are, in general, not processed independently [22, 29]. Virtual reality has, since its earliest days several decades ago, been dominated by visual stimuli with tactile and auditory information only recently becoming more mainstream. Despite the fact that our sense of smell, that is olfactory information, provides humans with a key source of environmental information, smell has largely been left out in virtual environments.

In this thesis, we consider the inclusion of this key human sense and show how its presence can provide an increased sense of "realism" in the virtual environment, and be exploited to selectively render visuals.

1.2 The Research Problem and its Importance

The research presented in this thesis investigates the problem of users demanding a high-quality multi-modal virtual environment in order to have a full "real-world experience" and achieve a feeling of being "there". The computational complexity of accurately simulating real-world environments is such that it is not possible to do this completely on existing computers. Methods, therefore, need to be developed which can reduce the computational requirements, without affecting the quality of the environment that the user perceives. One of the ways to do this is to exploit the limitations of the Human Visual System. It is well known that human eyes do not scan an environment "raster-fashion". Rather our eyes move in a series of jumps, or *saccades*, fixating on parts of the scene within the centre of our gaze, the *fovea*. Only objects located in the fovea can be perceived in full detail. Outside this region, visual acuity decreases. Therefore, if we know where the fovea is attending to in a scene at any point in time, only this area needs to be rendered at the highest quality. Furthermore, the presence of other sensory stimuli in an environment, or the task a user is undertaking, may also significantly influence how a user views a scene [27].

The goal of this thesis is to create 3D images and animations of the highest quality, while minimizing rendering time by exploiting the olfactory influence on the perception of an object or scene. In particular, we consider whether the presence of smell in a virtual environment may be exploited to significantly reduce the overall quality of the visuals that are delivered without a viewer being aware of a quality difference compared to a high-precision view.

Furthermore, we investigate whether a smell-emitting object (SEO) in a scene is highly salient and therefore automatically attracts the attention of the viewer. If so, then knowing where this SEO is can be exploited to reduce computational time even further more, by rendering where the SEO is in the highest quality (determined above) and the remainder of the scene in an even lower quality without the viewer being aware of this further reduction in the quality of the overall scene rendering.

In the real world, humans adapt to smells, that is, they fail to notice a smell after a certain exposure time to it. Smell adaption thus needs to be taken into account to ensure the selective rendering techniques that we propose are still effective once the user has been exposed to a smell for a certain time period. The impact of introducing other modalities to the environment in addition to smell, such as sound and temperature is also investigated.

1.3 Aims and Objectives of the Research

The main goal of this thesis is to understand better the influence of smell on users' perception of virtual environments. In addition, the thesis investigates the influence of single and multi-sensory stimuli on perceived visual quality and considers if these findings could be used for creating new perceptually-adaptive techniques that could deliver high-quality 3D graphics at a much reduced computational cost, when these multi-sensory stimuli are present, without any perceivable difference to the user.

The following are the objectives of this thesis:

- Investigate the olfactory influence on a user's perception of a computer generated image. Can smell be used to attract the user's attention to a smell emitting object in the scene and therefore allow us selectively to render the smell emitting object (eg. a bowl of flowers) in high-quality, and the rest of the scene at a much lower quality without the user being aware of this quality difference.

- Consider whether the presence of a related smell (smell of cut-grass) could be used to significantly reduce the level of detail in a real-time rendering animation of a grass terrain, without affecting the user's perception of a scene.

- Study the smell adaptation time period. Examine whether adaptation to smell affects the participants' perception and their performance within an environment when smell is present.

- Examine the influence of smell and other modalities such as sound and temperature on the viewer's perceived quality of a computer generated animation. Identify which combination of these modalities has a strongest impact on the participants.

1.4 Thesis Outline

The remainder of the thesis is organized as follows:

Chapters 2 and 3 provide an overview of previous research on Human Vision, Olfaction and Multi-Modal environment. These fields represent the background of the work explained in the rest of the thesis.

Chapter 2 gives a brief description of the Human Visual System (HVS). The retina, as one of the most important areas of the HVS, is also presented and described in this chapter. Furthermore, this chapter also provides information about attention and perception. General visual-attention processes are described, including the selectivity of attention in vision, the concept of inattentional blindness, and the voluntary/involuntary shift of attention. The chapter concludes with a brief description of attentional limitations that we tend to exploit for the purpose of this work.

Chapter 3 provides a detailed description of the Human Olfactory System, its structure and different components. We also describe the process of olfactory perception, which is composed of three basic tasks: intensity estimation, qualitative description, and hedonic tone perception. The close connection between olfaction and memory is also covered. The description of various Olfactory Displays and Electronic noses that have been developed is also given. In this chapter, we further provide a detailed review of previous research on the multi-modal virtual environments. While other senses such as vision, hearing and touch have been incorporated in virtual environments, there are only a few examples that mention the possible inclusion of smell.

The next chapters, Chapters 4 - 7, describe the experiments that were conducted: the design, procedure, participants and different conditions tested. The analysis and discussion of the results are also presented.

Chapter 8 represents a discussion on the results and findings bringing various elements together and providing implications of the work done.

Finally, in Chapter 9, conclusions are given and suggestions made for future work. More specifically, we outline and explain the thesis contribution to the computer-graphics research.

Appendix A presents the consent form used in all experiments, while Appendices B-D present questionnaires given to the participants throughout the experiments described in this thesis.

Chapter 2

Human Vision

The manner in which we see the world around us and the quality of that image/view is attributed to the neurology of the human visual system (HVS). Therefore, in this chapter we will focus on those areas of the human visual system that are relevant to our research. We will also point out to some of the known limitations of the human visual system including attentional and perceptual weaknesses which might be used in computer graphics for enhancing olfactory and visual rendering.

2.1 The Human Visual System

The human visual system is composed of three major parts as shown in Figure 2.1. They are responsible for viewing, analyzing, processing and identifying the world that surrounds us. Those parts are:

1. **The Eye**, represents the first point of contact for the visual system. It is slightly asymmetrical with a diameter of around 24mm [148]. A cross-sectional view of the eye shows that it is composed of three layers: the sclera (exterior layer), the choroid (intermediate) and the retina (internal)(Figure 2.2) [94, 111]. The sclera is the white part of the eye, the "shell of the eye", that supports the eyeball. The choroid lies between the sclera and retina and provides oxygen and nutrition to the inner layer of the retina. The retina covers the largest area of the eye, and is the area where light is detected and further processed. It is considered to be the most important part of the eye and as such, will be described in more detail in the following section.

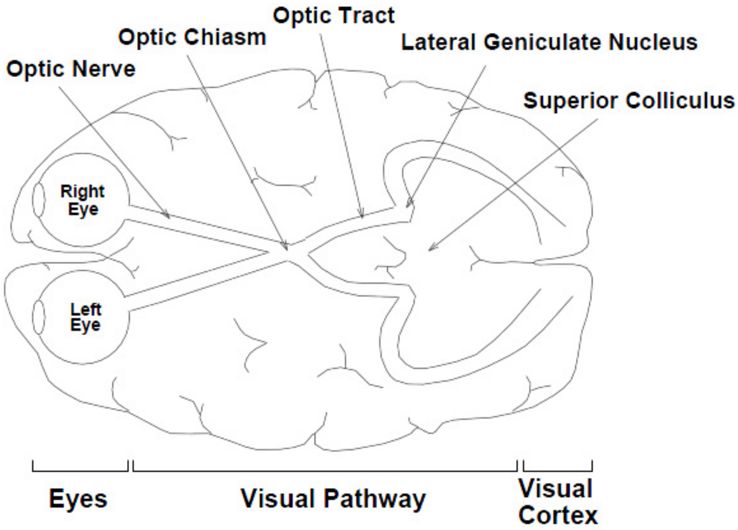

Figure 2.1: Top view of the brain showing the three main processing parts of the human visual system [148].

The cornea is the front part of the eye. Light enters the lens through the cornea and pupil (Figure 2.2). The amount of light is one of the factors that determine the size of the pupil, which is controlled by two sets of muscles, one for decreasing and one for increasing the opening. The size of the pupil also affects the depth of field and as such is similar to aperture size in photography. The crystalline lens is a transparent structure of the eye that helps refract the light, focusing it on the retina. By changing its shape, the lens helps the eye to focus on an object of interest at various distances and thereby form a sharp real image in a retina. This process is called accommodation [16].

2. **Visual pathways**, which link the eye to the brain (one for each eye). They transfer an encoding of the light to the higher vision centre of the brain. Processing and re-organization of the carried signals happens during this stage. The visual pathway is composed of two main parts: superior colliculus and the lateral geniculate nucleus (LGN), see Figure 2.1 [148]. The superior colliculus represents a very complex structure composed of many layers. However, its main function is inducement and control of eye movement. It is often described as a "visual reflex centre". The LGN represents the main area where processing

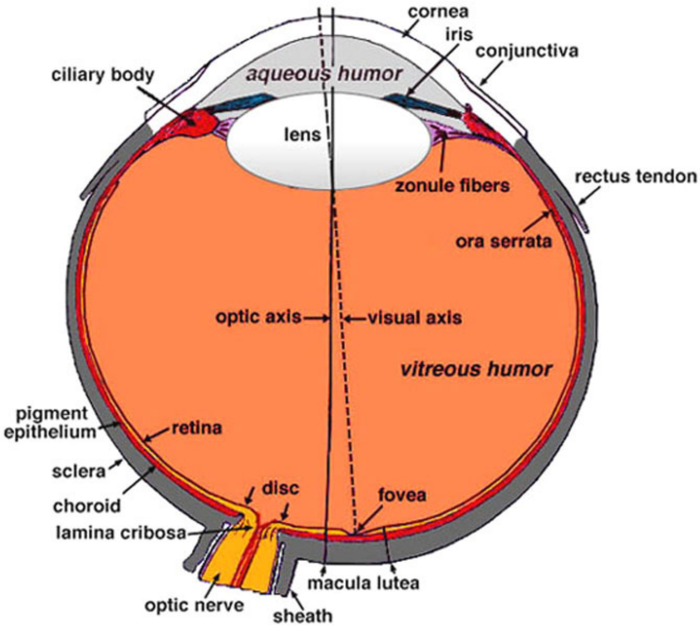

Figure 2.2: Sectional view of the eye [94].

of information received from the retina of the eye occurs. There are two nuclei, one for each eye, from which LGN receives information. Right and left LGN exchange information about opposite visual fields.

3. **The visual cortex**, which is located in the lower rear of the brain and is responsible for processing all the information that the brain receives [111, 148]. This information is transmitted directly from the eyeballs through the LGN to the visual cortex. This process is known as optic radiation. This area of the brain can be further divided into 5 areas (V1, V2, V3, V4 and MT), of which V1, sometimes called primary visual cortex, is the largest and considered to be the most important.

2.1.1 The Retina

The retina is located at the back of the eye and covers around 65% of its surface. It represents a very complex structure, but its two main parts are the ganglion cells and photoreceptor cells. Ganglion cells represent the output neurons of the retina and are located closer to the front of the eye. Photoreceptors are divided into rods and cones and lie near the pigment epithelium and choroid, see Figure 2.3 [111, 148].

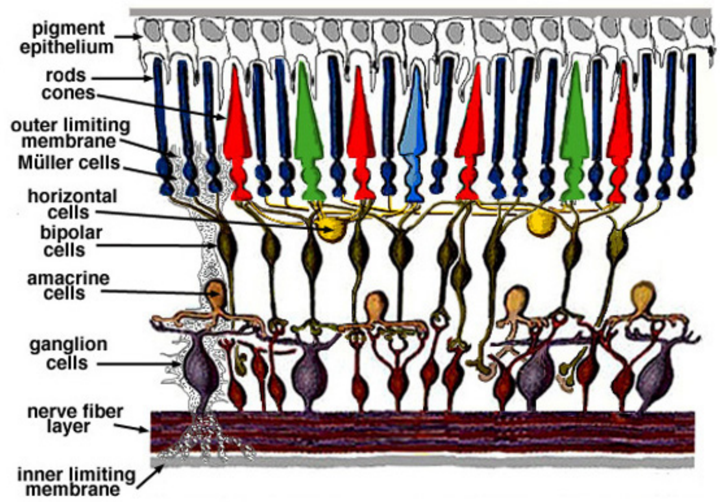

Figure 2.3: The view of the retina [94].

An image comes through the eye, stops in the retina which converts it into electrical signals and sends it to the brain via the optic nerve. The conversion of the signals is done by rods and cones. Rods are unable to distinguish colour, are very sensitive to light and therefore mainly function in low light conditions, telling us only what sort of shape an object has. Cones, on the other hand, function in daylight conditions and provide us with colour vision. There are three types of cones, usually known as red, green and blue which allow us to see a wide range of colours (see Figure 2.4). They are also known as long (L), middle (M) and short (S) wavelength sensitive cones [111]. Only 5% concentration of S cones are found in the retina [157]. The rest (95%) is occupied by L and M cones. However, lack of any of these kinds of cone can result in colour blindness. Even though we can perceive millions of colours, there is only a limited number that we can actually name and recall [111, 148].

In the centre of the retina is the fovea - the area most sensitive to light and responsible for sharp eye vision [94]. The concentration of cones is highest in this region, while rods are mostly located in the peripheral retina. There are around 100 million

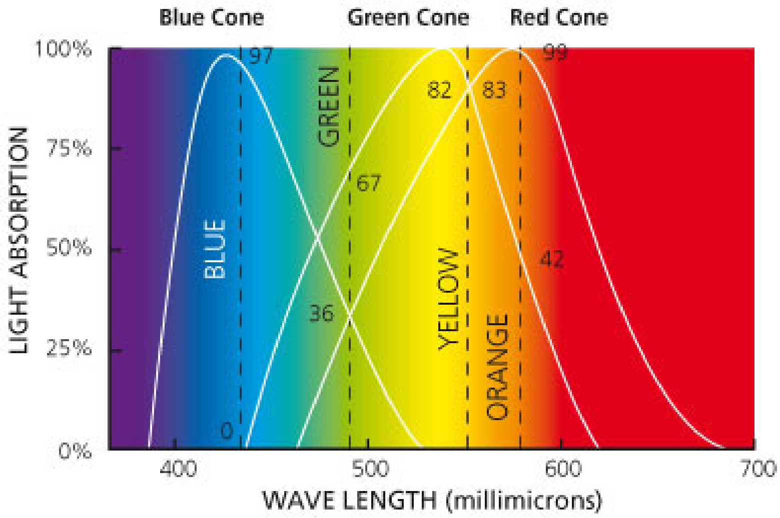

Figure 2.4: Spectral sensitivity of cones [165].

rods and only 5 million cones in the human retina [157]. The different concentration of rods and cones is shown in Figure 2.5. The number of optic nerves that carries an image through the retina to the brain is around 1.2 million [157].

2.2 Visual Perception

Visual acuity is directly proportional to the size of the object in the scene and indirectly proportional to the distance from that object. The fovea region, which has the highest concentration of photoreceptors, has the highest visual acuity. As we move further away, the acuity decreases. Therefore, the Human Visual System is incapable of capturing and processing a scene in full detail. The human centre of gaze (area of the fovea vision) covers only 2 degrees of the viewing field. This means that only the objects/images that fall within this viewing field are recognizable and contain the highest quality visual information. Similarly, objects located outside this region are generally not recognized or at least not identified to the same level of precision. However, the entire scene can be seen with head and eye movement in a particular direction, so called saccades. Research has shown that we move our eyes three times per second when viewing a scene [71].

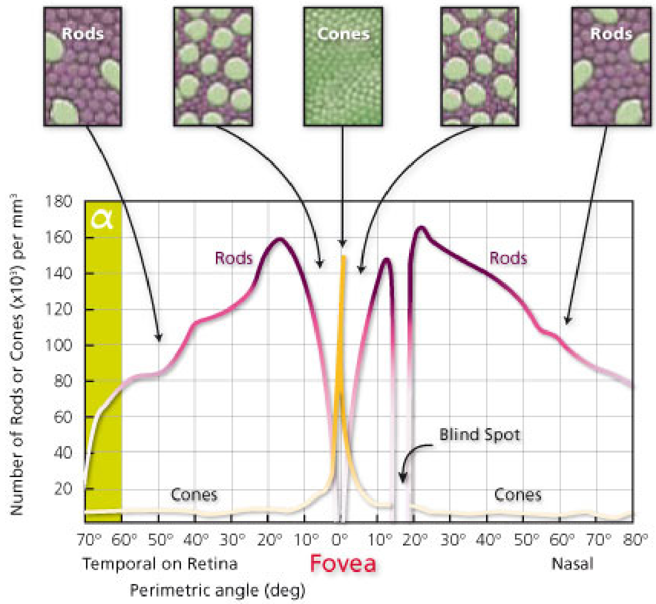

Figure 2.5: Different concentration of photoreceptor cells in the retina [165].

Visual perception is an increasingly important area of research in computer graphics. Its integration has altered both fields. As [Bartz et al.] wrote, "it offered new research questions, but also new ways of solving existing issues" [11]. Ittelson stated "perception is an interactive process of information exchange between participant and environment" [82] (also in [136]). It gives sense to what is observed.

Therefore, the ability to perceive an object in full detail and high quality can be divided into three groups, depending on the external stimuli, such as an object being in motion. These groups are spatial resolution, temporal sensitivity and retinal inhomegenity.

2.2.1 Spatial Resolution

Spatial resolution refers to the ability to detect the smallest object in front of us. How small the object can be in order for us to identify it depends on the size of the receptive field, which varies throughout all major parts of the visual system, as described previously. For example, "the human eye can detect details to the size of about 0.5 min of an arc ($\leq 0.01°$) because in the most dense packed region of the retina, the limit for the size of the stimulus is given by 0.5 min of arc" [94].

2.2.2 Temporal Sensitivity

Temporal sensitivity represents an amount of detail that can be captured in a moving image with respect to time [148]. For example, by looking at an object in motion, we are not able to achieve the same visual acuity as with an object standing still. However, our eyes are constantly recording and sampling the real environment. The gathered information is then summed up so the object in our field of view would appear as being stable or moving fluently.

2.2.3 Retinal Inhomegenity

The concentration of photoreceptor cells is not the same across the entire region of the retina. As we mentioned earlier, the highest concentration of cones is in the fovea, and this concentration falls drastically as we move away from the fovea. The opposite case is with rod cells. Furthermore, the periphery region is far more sensitive to motion compared to the inner area, which is more sensitive to details [111, 148].

The maximum sensitivity of the human vision is achieved in the central part of vision, the fovea region. The capture of any detail or motion outside this region, requires head and eye movement [111, 148].

2.3 Attention and Perception

Attention is a mechanism that determines what part of the scene we focus on and what we ignore [22, 29]. It also determines which sensory stimuli will be further processed by the brain, and again, which will be ignored. Metaphors used to describe the term "attention" across literature are: spotlight [140, 180, 200], a zoom lens [57], or a filter [22]. Attention, besides being able to focus our gaze on a particular object, can also narrow our view area or make it wider [139]. Usually, the focused area is small and if there is a certain movement involved (e.g. use of joystick while playing computer games), it is even smaller. Another example would be watching a live football match. If the focus of attention is not on the ball, there is a great chance that we will miss a goal scored.

In fact, in 1907 Bàlint stated that "It is a well-known phenomenon that we do not notice anything happening in our surroundings while being absorbed in the inspection of something; focusing our attention on a certain object may happen to such an extent that we cannot perceive other objects placed in the peripheral parts of our visual field, although the light rays they emit arrive completely at the visual sphere of the cerebral cortex." [80] and also in [167].

William James in his book Psychology defined perception as "the consciousness of particular material things present to sense" [86]. In fact, several psychological surveys have proved that stimuli reaching the various senses are, in general, not processed independently [14, 15, 22, 29]. A similar result was also achieved by Tellinghuisen and Novak [179]. This is called inattentional blindness, meaning "that there is no conscious perception without attention". In their study, Mack and Rock reported that the perception of shape requires attention, while perception of colour, location, motion does not [110]. They are perceived without attention.

Furthermore, perception can also be shaped by learning, memory and expectation [13, 65]. We are constantly surrounded by an overwhelming amount of information which affects all our senses. Despite this, we are constantly able to interpret what we see. Attention is what helps us in this process, by enhancing the relevant information and ignoring or under-presenting the rest.

2.3.1 Attention: Automatic and Voluntary Control

There are two general visual attention processes known as the bottom-up and top-down approach, which determine where humans focus their visual attention [85]. Bottom-up is an automatic visual stimulus, fast, not dependent on cognition or task demands. Top down, on the other hand, is voluntary and focuses on the observer's goal [43, 83]. An example of bottom-up would be a candle burning in a dark room and of top-down looking for a street sign or a target in a computer game [210]. Furthermore, active attention, also known as endogenous attention, is when we concentrate in order to understand, for example, from where a particular smell is coming in the sea of various smells while in the market. This is an example of a top-down control. The opposite to this is a passive or exogenous attention, where we have a bottom-up control. An example of this would be the sound of a car accident, which will make us immediately attend in that direction [159]. Another example would be the results of a study done by Yarbus [209] where participants failed to notice anything outside the task-given region. Therefore, exogenous attention is dependent on colour, intensity, orientation and direction of movement, which form topographical, cortical maps called feature maps [92]. Saliency map is formed by combining these maps. It is used to predict where user will focus his/her attention in an image. A computer generation of the model for static images was developed by Itti et al. while Yee et al. created an extended version of the framework using Aleph map and including the temporal component.

When speaking about attention capturing, generally two terms are used: explicit attentional capture and implicit [166]. The former occurs when a certain object outside our visual focus attracts our visual attention, while the latter occurs when an irrelevant object affects our primary task. An example of explicit attention capturing is inattentional blindness. In experiments reported by Mack and Rock, participants were asked to report if they saw anything else besides the cross at which the focus of attention was placed. Between 60% and 80% of participants failed to report seeing other objects, beside the cross itself. Interestingly, participants tend to notice their name and a smiley face even though they are focussed on a different task [110, 167]. Besides our names, people seem to respond more quickly even to words such as "rape", compared to more common and neutral words [38]. In another experiment done by Simons and Chabris, participants failed to notice a gorilla or a woman with an umbrella passing through the scene, while they were focussing on a white or black basketball team and how many shots they made [167]. The videos in the experiment were not computer generated (Figure 2.6).

According to Rensink, we can only focus on a single object at any point in time. Viewing other parts of the scene requires the shift of attention in that particular direction [150]. Shift of visual attention can be central or peripheral [140, 207, 208]. Central is when we decide to move our attention from one point to another while peripheral is when a certain event happens and captures our attention automati-

Figure 2.6: Single frames from the animation used in the experiment by [167].

cally. Usually, we focus our visual attention on the most interesting object in the scene, which may be familiar, or just the most salient one (eg. a red jacket among black and white tuxedos).

2.3.2 Attentional Limitations

As mentioned earlier, we are not able to fully perceive all information attacking our senses. Only those that are relevant and of interest at that particular moment will be interpreted and processed. Beside physical limitations, there are also limitations with regard to memory and attention overload. We can only store up to 5 different "chunks" of information in visual short-term memory [81,106]. Luck and colleagues showed that we do not store in visual memory a single feature of a object, but rather complete information such as colour, shape and position of a particular object [106]. Furthermore, we also need to shift our attention in order to perceive the scene fully, as it has been shown that the maximum span of attention is even lower, 1 degree of visual angle [55,56]. Eriksen et al., through a series of experimental studies, also showed that the visual attention focus could be changed [56]. However, with increased attention field, we decrease the number of processing resources within that particular field.

Furthermore, researchers are still not sure whether these resources are shared amongst fields (i.e. modalities) (inter-modal) or are they individual (intra-modal). Example of inter-modal can be seen in work by Strayer et al. who demonstrated that talking on a mobile-phone affects driving performance due to shift of attention from the primary task (driving) [175, 176]. Participants missed twice as many simulated traffic signals when talking on the phone, and took longer to react on those signals that they did see. Strayer et al. conclude that “conversing on either a handheld or a handsfree cell phone leads to significant decrements in simulated-driving performance.” However, this was not the case with other tasks such as listening to a radio station or a book recorded on a tape.

An intra-modal example is given in research by [3] on vision and audition, where they claim that there is no attentional dependencies between these two modalities when dealing with low-level tasks, such as discrimination of pitch and contrast. However, their work revealed that there might be some attentional limitations within the modality itself when performing a dual-task. Similar results can be found in [25,49].

The way experiments were set-up might be one of the reasons for these different findings. In the first group [175, 176], participants were directing their attention to different spatial locations while in the second group (eg. [25]) attention was spread out across the entire sensory field, with minimum change in spatial location of the simulated regions.

Chapter 3

Olfaction - Sense of Smell

The sense of smell is a primal chemical sense for humans. We are constantly testing the quality of the air we breathe and it also informs us of other environmental information, such as the presence of food, freshly brewed coffee, a fire breaking out in the next room, leaking gas or another individual, as research has recently shown [84, 88, 121, 129]. Recent research has also shown that every individual has a unique smell and therefore can be recognized by that smell [84]. Kerstin et al. showed that women can recognize the smell of fear in the armpit secretions of people who watched a frightening movie [89]. They believe it is not due to changes in the cortisol levels but rather that "hypothetical fear pheromone" has some other origin which still needs to be identified.

The odour emitted by a patient may be one of the early and therefore very important clues of various diseases such as cancer, schizophrenia [103, 121]. In extensive research by [42] on 750 patients with a primarily olfactory problem, 68% reported that their disfunction significantly altered their life, 46% said that the disorder affected either their appetite or body weight and 56% complained that it influenced their daily living and/or psychological well-being. Miwa and colleagues also showed that the olfactory problem can decrease the quality of life [117].

Even though sense of smell adds richness to our lives, it is mostly regarded as a minor sensory modality and until recently, largely ignored by researchers. Scientists are still exploring how, precisely, we smell, how we notice, process and interpret odorants as odours, where an odorant is a "substance capable of provoking an olfactory response" and odour, "sensation resulting from stimulation of the olfactory organs" [48, 141].

3.1 The Human Olfactory System

Smell being a very direct sense implies that in order for us to smell something, the molecules of the particular object will have to reach our nose. Everything we smell is giving off molecules: fresh bread in a bakery, hot pizza, flowers, and so on. But, in order for a substance to be recognized as an odour by the receptor cells, it has to have certain molecular properties [99, 141]:

- the substance must be volatile enough to float through air into our nose. For example, steel has no smell because it is a non-volatile solid,
- the substance must be capable of dissolving in water and thus able to pass through the mucus layer and to the olfactory cells,
- the substance must be capable of dissolving in fat since olfactory cilia are mostly composed of lipid material.

Odorants represent volatile chemical compounds with low molecular weight (30-300 [Dalton]) that are carried by inhaled air to the regio olfactoria (olfactory epithelium), the region located at the top of the two nasal cavities, just above and behind the nose, in the middle of the face (Figure 3.1) [67, 99].

The olfactory region is composed of cilia lying in a 60 micron thick mucus layer. Cilia are connected to the olfactory epithelium. The mucus layer is produced by Bowman's glands situated in the olfactory mucosa, below the olfactory epithelium. With the help of mucus lipids our brain interprets biochemical and electrical signals as odours. Those signals are created after chemical stimuli reaches the olfactory receptor neurons. Keyhani and colleagues developed a numerical model of transport and uptake of inhaled odorants in the human nasal cavity [90]. They were the first to provide detailed information about odorant flux across the two-dimensional surface of the human olfactory mucosa.

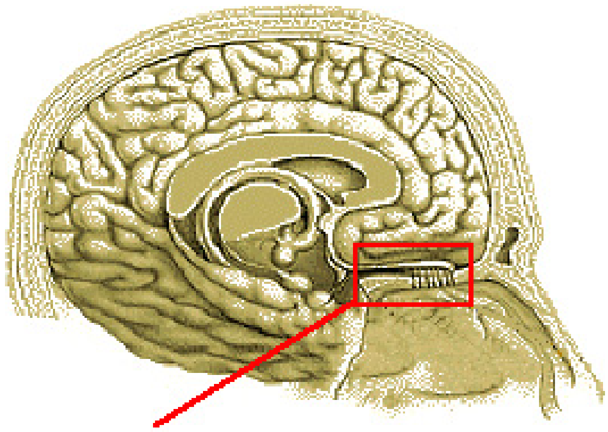

Figure 3.1: The olfactory region [99].

Each olfactory receptor neuron has 8-20 cilia that are hair-like extensions, 30-200 microns in length. The olfactory cilia are responsible for transmitting the odour to the olfactory nerve, which then sends it to the brain [99]. In addition to the cilia, there is also a fifth cranial nerve called the trigeminal which has free nerve endings spread throughout the nasal passage. These nerves react to very strong and irritating smells such as detergents, pepper and so on [152, 212].

As mentioned earlier, the olfactory epithelium is situated just above the mucus layer and covers a surface of about $3cm^2$. It is composed of: the olfactory receptors, the supporting cells, and the basal epithelia cells [128]. The olfactory receptors are located above the mucus layer (see Figure 3.2) and are composed of two discrete segments, each accessed from a single nostril i.e. left or right [97, 171].

Each segment is covered with a layer of mucus that is essential for normal function [132]. The basal epithelium cells are capable of creating new olfactory receptor neurons. Each new neuron possesses the same cellular properties such as odour sensitivity, odour preferences and axonal projection as the previous neuron [39]. The lifetime of a single olfactory receptor neuron is around 30-40 days [128].

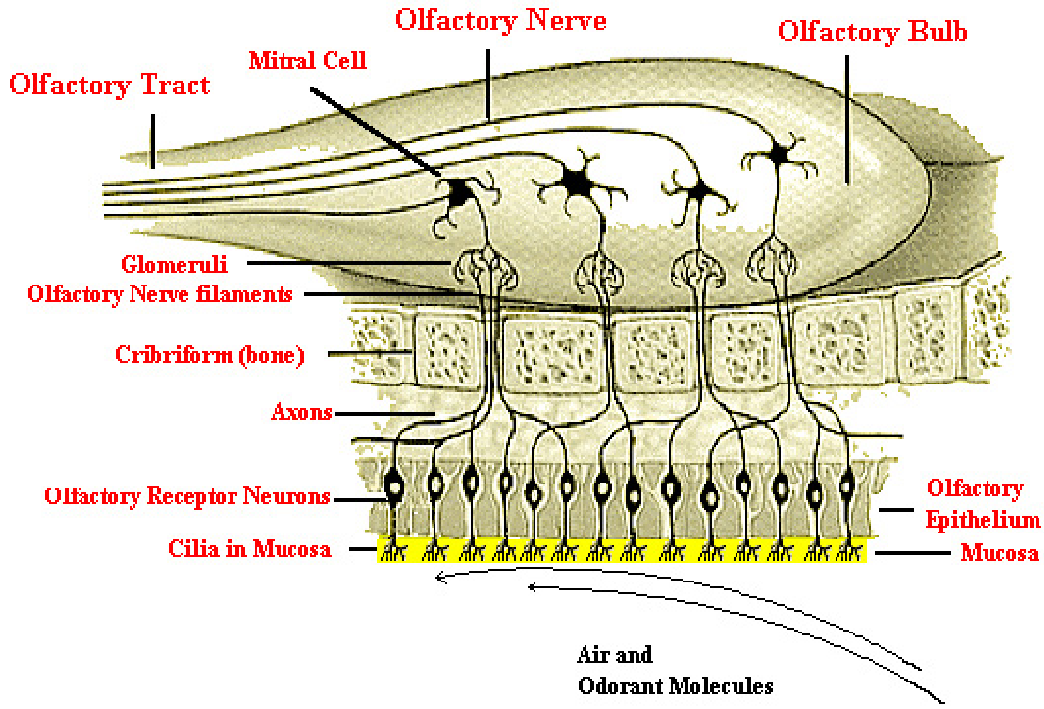

Figure 3.2: The olfactory epithelium [99].

The olfactory receptor neurons are surrounded by the mucus layer on one side and, as such, are directly exposed to the external environment. On the other side, we have the neuronal cells, which form axons that are joined into groups of 10-100 that penetrate the cribriform (bone) in order to reach the tiny regions of the olfactory bulb called glomeruli. The glomeruli further converge into mitral cells. This convergence increases the sensitivity of the olfactory signal sent to the brain. From the mitral cells and through the olfactory nerve track, the signal is sent to the amygdala part of the brain for decoding, interpreting the odour and producing an adequate response [99]. There are around 2,000 glomeruli in the olfactory bulb, allowing us to perceive a huge range of smells because each odour activates a different pattern of glomeruli. This pattern depends on the airflow rate and odour concentration. The olfactory bulb is part of the limbic system, composed of the amygdala and hippocampus which are primarily responsible for our emotional life, behaviour, mood and memory [48].

One of the leading issues in current olfactory research is still how the brain differentiates one smell from the other [197]. In 1991, Richard Axel and Linda Buck published a key paper on how the brain interprets smell and in 2004, won a Nobel Prize in Medicine for the paper and their independent research. They reported that olfactory receptors belong to a large family of molecules called G-proteins and that every receptor cell has only one type of receptor which can detect a certain number of molecules and respond to them [24]. It is now known that there are about 350 odorant receptor genes and about 560 odorant receptor pseudogenes in humans. This number of genes and pseudogenes, specific only to the olfactory system, embraces nearly 2% of around 50,000 genes of the human genome. All other senses occupy much smaller regions [24, 99, 171].

Each odorant is recognized by a different gene and, it is believed that there are around a hundred million receptor cells in the human body. If we are missing a single gene, that could lead to a lack of olfaction to that particular smell. For example, some people have no sense of smell for "camphor" [48]. Furthermore, a tiny change in the molecular structure of an odorant may lead to a perception of a completely different odour [24].

The vast number of theories used to describe the mechanism of smelling odours can be classified in two groups: physical theory and chemical theory [141]. The physical theory indicates that each molecule of an odour and its particular shape simulates a different olfactory cell and therefore, a unique odour is perceived. However, scientists reported that some molecules with nearly the same shape smell nothing alike [213]. Among researchers, the chemical theory is more accepted. According to this theory, "the odorant molecules merge chemically to protein receptors in the membranes of the olfactory cilia. The type of receptor in each olfactory cell determines the type of stimulant that will enhance the cell. Attaching to the receptor indirectly creates a receptor potential in the olfactory cell that generates impulses in the olfactory nerve fibers" [141].

A great deal of evidence indicates that the olfactory system is like a "tabula rasa", in which the meanings of odours are acquired throughout an entire life. And, as Engen has said: "perhaps the major function of olfaction is to store odour experiences and associated events in memory for future use" [53].

3.2 Odour Perception and Physiological Response

Olfactory perception is composed of three basic tasks: intensity estimation, qualitative description, and hedonic tone [68]. One of the most significant features of olfaction is the high sensitivity and thus low detection threshold. Certain odours in air can be detected, but not identified ("I smell something") at very low concentrations such as 4×10^{-15}g/L and are identified at 2×10^{-13}g/L [128]. These numbers represent an estimate due to high diversity of population but in general may differ by a maximum of 50-fold [52, 162].

On the other hand, qualitative description of an odour still remains a difficult task, mostly because humans have the ability to discriminate up to 10,000 different odorants (compared to vision where we have only four different kinds of receptors) [88, 162]. Various schemes have been proposed in the past in an attempt to classify odours into smaller groups. The first such attempt was made by Amoore, who proposed 7 primary odours because of their high frequency of occurrence amongst 600 organic compounds: camphor, musk, floral, peppermint, ether, pungent and putrid [6, 84]. Rimmel proposed a more general classification system which included 18 categories, while a more abstract system was proposed by Zwaardemaker that included only 9 main categories, each of which was further divided into two or more categories (see [119]). Henning's odour prism represents an attempt to identify primary odours (equivalent to red, green and blue colours) [72]. Each corner of the prism represents a primary quality: fragrant, putrid, ethereal, spicy, burnt and resinous (see Figure 3.3).

Henning claimed that odours would either be fully captured by a primary odour descriptor or fall on the surface or edges of the prism if in between categories. This assumption caused a huge number of researchers to run various experiments, concluding that many odours could not be located on the surface of the prism [59, 69, 109]. For example, in MacDonald's study, geraniol was reported to have three principal qualities (flowery, fruity and resinous) but according to the prism, it should also have a spicy quality; therefore, participants' judgments were not in accordance with Henning's solution [109, 171]. Due to the lack of success of these classification theo-

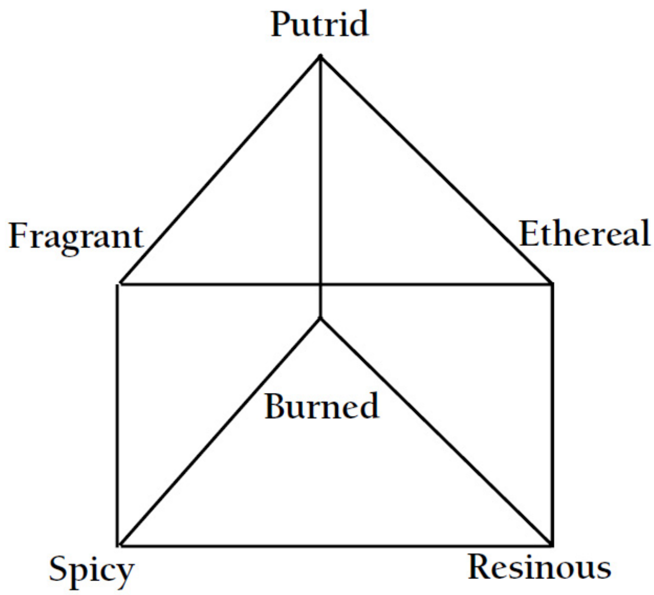

Figure 3.3: Henning's smell prism [142].

ries, current approaches employ odour profiling techniques, in which a large number of verbal descriptors are used to describe individual odours adequately, if at all possible [68, 162]. Needless to say, the use of verbal descriptors assumes participants have the same olfactory experience and that they will use the same words in the same way to describe a particular odour [199]. Furthermore, odours that are nameable are almost by definition highly familiar [170]. Individual differences in reception are very much influenced by individual differences in cognition, culture and experience [201]. This would seem to suggest that there are no primary odour qualities (for a similar conclusion see [35, 171]).

The third task of olfactory perception, the hedonic tone, represents a qualitative property according to which odours are further divided into two groups: pleasant (positive hedonic value) and unpleasant (negative hedonic value). The hedonic quality is highly subjective and is influenced by our cultural background and emotions [156,197]. Whether a person likes an odour or not depends largely on the association made through life. In addition, some odours are considered pleasant at low concentrations and not at high, meaning that the hedonic tone is non-monotonically dependent on the exposure level [67]. Differences in odour perception across cultures may be significant, since cultures differ in their use of various flavours, specific odours and in their use of odorants in different contexts (eg., cleaning detergents, perfumes, and so on) [120, 171].

Koelega and Köster reported that there is a significant difference between sexes in the hedonic perception of smell and also in sensitivity to an odour [93]. This was also shown by [101]. However, various researchers have reported that men are more likely to guess, compared to women who will not report a smell being present unless absolutely sure [93, 101, 114, 187]. Such responses may significantly affect experimental results and future research directions. Furthermore, scientists have shown that changes in the ability to perceive odours, which are known to occur in elderly people, are greater in men than in women [42]. This was also shown by [47, 95].

Psychophysiological studies exposing subjects to pleasant and unpleasant odours suggest that the hedonic factor is of significant influence, and that odours are processed differently depending on the hedonic tone. For example, perception of unpleasant odours produces "automatic emotional arousal as indicated by the measures of skin conductance and heart rate" [4,5,155]. There is evidence that pleasant ambient odour has a positive effect on relieving stress and improving mental relaxation. For example, in the area of aromatherapy, essential oils are being used allegedly to help people relax and release the stress they accrue doing their everyday jobs. It may be beneficial to introduce olfactory stimulation as a treatment. For example, the experiment conducted by Lehrner et al. suggests that an ambient odour of orange in a dental office could reduce anxiety and improve mood in female patients [100]. Numerous studies indicate that unpleasant odours produce a much higher degree of activation and leave a deeper/longer lasting impression than pleasant odours [95].

Recognized odours may affect our mood and they can have a psychological impact on the olfactory system. People associate odours with past experiences and odour perception is influenced by learning, and relies much more on experience than do other senses [31, 138]. Like and dislike of a particular odour may change depending on odour concentration or intensity [141]. On the other hand, our olfactory experience and knowledge progressively improves, especially through adolescence and early adulthood [195, 196]. Barfield and Danas reported that peak performance in olfactory identification occurs between the third and fourth decade of life [10]. For vision and audition, major developmental changes such as object discrimination, hearing threshold, colour and depth perception are nearly complete by the age of one [171]. Even though olfactory sensitivity (which depends on the duration of stimulation and concentration [26]) gradually but steadily declines with age [42,101,186], it has been shown that pleasant fragrances have positive effects across all age groups. However, even though there is strong evidence that a pleasant smell can improve our mood and our sense of well-being, researchers also found that just by telling participants that a pleasant or unpleasant odour was being used in the study, which they might not be able to smell, altered their reports of mood and well-being [60]. In an interesting research done by Stockhorst and colleagues, insulin was injected into healthy male volunteers once a day for four days and their blood glucose was measured (it fell). At the same time, they were exposed to a smell. On the fifth day they were just given the smell, and their blood glucose again fell [173].

Even though we may learn to discriminate different odours with age and experience (eg., wine tasters), we are still not able to separate an odorant from a mixture of more components [67]. We may never be able to do so due to the nature of our olfactory information processing [78, 171]. However, one of the important characteristics of olfaction is the ability of an odour to evoke an old memory as if it was a current moment. This phenomenon might be described as an implicit memory effect on perception [169].

3.3 Olfaction and Memory

Smell and memory are closely linked. The olfactory bulb is part of the brain's limbic system, the area associated with memory and feelings and very often referred to as the "emotional brain". Smell can evoke strong emotional reactions, create moods and influence feeling [23,48,50,60,107,182,190]. Our ability to detect an odour will not be lost with the injury of the temporal cortical region of the brain, also known as the site of memory, but rather our ability to identify a smell. In order to recognize a smell, one must first remember [84]. Our sense of smell can enable us to remember an event we may have forgotten, and the smell of a certain perfume or cologne can remind us of a particular person. According to Osuna, memories evoked by other senses are not as strong and emotional as those triggered by smell [67]. Herz and

Cupchik also reported that odour-triggered memories tend to be highly emotional, vivid and specific [73, 74]. In other research, Herz and Eich presented a number of arguments to support their claim that olfactory memory is different from verbal memory [75]. The relationship between memory and smell is:

- Memory: odour memory falls off less rapidly than other sensory memory and is unique compared to memory in other sensory modalities [98, 115].
- The "Proust effect": an odour associated with an experience and a smell can recall the memory; smell is better at this memory cue effect than other senses [37].

The largest smell survey, the National Geographic survey, gave readers a set of six odours on scratch-and-sniff cards. From a sample of 26,200 respondents, 55% of respondents in their 20s reported at least one vivid memory cued by one of the six odours and only 30% in their 80s did the same [63]. Furthermore, research has shown that short-term visual recognition produces 100% correct answers, as opposed to 70% when odour is used. However, studies show that olfactory information is longer lasting in our memory than other types of stimuli which degrade over the years [37]. For example, even one year after, no significant decrease in odour recognition performance was noted in the study presented by [54].

In a recent experiment, participants were presented with three stimuli: visual (an image of an object), lexical (the name of an object) and olfactory (the odour of an object). They were asked to write down whatever they could think of in regard to the presented stimuli. The responses to the visual and lexical were longer but less emotional than those given for olfactory stimuli. Those responses referred to memories [60]. Since we encounter most odours for the first time in our youth, smells often evoke childhood memories.

Research has shown that smell can also affect product judgments [18, 76]. For instance, 22 of 35 participants liked the Nike shoes better in a room with floral ambient scent than in a non-odorized room [76, 116]. However, more profound research is needed to completely understand olfactory cues and their impact on different products under different environments. Interestingly, buying behaviour can also be stimulated. Adding some aromas to the air lengthens customers' shopping time by 16 %, makes them 15 % more willing to buy, and increases sales by 6 % [161].

The role of olfaction in learning and memory has been found useful in training people in various areas. Examples include the recognition of chemical reactions by olfaction rather than sight and for increasing recall, recognition, attention, performance, and productivity [87]. One of these factors, performance, was tested in the presence of smell in the study presented in Chapter 6.

Ambient odours of lavender and lemon introduced during the encoding process improved free recall, word recognition, and performance on spatial learning tasks in subsequent trials for four weeks after the initial introduction [122]. Smell of lemon represents one of the most common smell used in the household and as such was used also in studies presented in Chapter 6.

3.4 Olfactory Displays and Electronic Noses

Smell represents an under-used and almost unexplored medium [12, 88]. There are various reasons for this, such as no adequate technical solution for emitting scents, the problem of creating accurate scents when knowing that a human nose can recognize up to 10,000 different molecules, delivering on demand, and so on [36, 88].

Even though the final output of this thesis will not be the development of olfactory display nor electronic noses, the main advances so far will be explained here in brief for completeness.

The electronic nose was developed in an attempt to simulate the human sense of smell [143]. The difference between the two is illustrated in Figure 3.4. However, available electronic noses are no more sensitive than an ordinary human nose. Their advantage lies in the fact that they do not get bored after the repetitive task of smelling various odours and that they don't need a break due to adaptation to particular odours. Unpleasant odours do not make electronic sniffers feel ill and they are not affected by common but also unpredictable human factors such as mood, hormone cycles and so on [60]. On the other hand, response time for an electronic nose ranges from seconds to a few minutes, which represents a significant drawback [40]. However, they are frequently used in the food, beverage, and perfume industries for product development and quality control, medical diagnosis and environmental monitoring [40, 143]. More recently, University of California San Diego Jacobs School of Engineering announced the development of an optimized component that can select and release scents from 10,000 odours, and is intended to be part of a Digital scent solution for TVs and phones in the future [91]. Furthermore, as reported by NASA researcher, Dr.Ryan, in essence electronic noses can be used to identify substances whose patterns are already known. However, a step forward would be the development of a successful computer model that could help an electronic nose identify unknown compounds as well [127].

HUMAN	ELECTRONIC
~ 10 million receptors, self generated	5-100 chemical sensors manually replaced
10-100 selectivity classes	5~100 selectivity patterns
Initial reduction of number of signals (~1000 to 1)	"smart" sensor arrays can mimic this?
Adaptive	Perhaps possible
Saturates	Persistent
Signal treatment in real time	Pattern recognition hardware may do this
Identifies a large number of odours	Has to be trained for each application
Cannot detect some simple molecules	Can detect also simple molecules (H_2, H_20, $C0_2$…)
Detects some specific molecules	Not possible in general at very low concentrations
Associative with sound, vision, experience, etc	Multisensor systems possible
Can get "infected"	Can get poisoned

Figure 3.4: The comparison between human and electronic noses [40].

Barfield and Danas define olfactory displays as a "collection of hardware, software, and chemicals that can be used to present olfactory information to the virtual environment participant" [10]. When creating an olfactory display, certain factors such as directionality, portability and operating capacity must be taken into account [212]. Directionality refers to the process of detecting the smell in the environment while portability means that the display must be mobile, in order to easily allow and accept all kinds of movement. Operating capacity refers to the fact that the odour cartridge must be replaced after a certain period of time and is therefore directly connected to the portability issue.

The two general types of olfactory displays are: ubiquitous and wearable. The first known display was developed by Cater and a group of researchers at the Deep Immersion Virtual Environment Laboratory (DIVE) at the Southwest Research Institute in San Antonio, Texas. It was called DIVEpak, controlled by a microcomputer and was able to deliver eight odours [211].

ART Media Information Science Laboratories created an easily controllable olfactory display that uses an “air cannon” to deliver scent near the user’s nose [203–205]. The system detects the position of a user’s nose with the help of computer-based face tracking technology. In this particular case, users can enjoy the scent without having to wear anything on their faces. However, their movement is reduced as they cannot walk outside (i.e. outdoors). Yamada et al. created a wearable type of olfactory display: “direct-injection wearable olfactory display” [202]. The system injects odour molecules directly to or near the user’s nose.

One of the most important functions of an olfactory display is the ability to present a variety of smells [123–125]. A variety of smells can be generated with the help of a blending function [123]. There are several types of olfactory displays with the function of blending component odours: Mass Flow Controllers (MFC), inkjet devices and solenoid valves [126]. An MFC is used to electrically control the flow rate without the influence of the pressure load. It is useful for controlling the flow rate accurately but too expensive for blending many odour components. The inkjet device was originally developed for printers and requires skill to handle. Solenoid valves are cheap and easy to handle. They are also stable and relatively small, and thus suitable for integration in order to achieve an olfactory display with a large number of odours [125]. A solenoid valve is a fluidic switching device with only two states: ON and OFF. The high-speed switching enables any concentration, since the frequency of the ON state corresponds to the odour concentration. Nakamoto et al. initially developed an olfactory display that could only blend 8 component odours and produced a movie with odours. Results of their study indicate that the scenes with smell attracted people’s attention and moreover, that the contrast of the pleasant smell with the unpleasant one emphasized their attention [126]. In 2007, the same group of researchers presented an olfactory display that could blend 31 component odours [123]. The size was unchanged (size of a laptop computer) even though the number of odours was four times larger than was the case for the previous version. 256 combinations were possible with the 8 odour components, while approximately 2×10^9 combinations are possible in the case of 31 odour components.

In 2003, Tijou et al. developed a DIODE project that enables olfactory feedback [181]. The user, wearing a head-mounted display (HMD), navigates through the Vendome Square in Paris and as he/she moves, a smell corresponding to a particular object, eg. the smell of a Christmas tree, the smell of a rose and/or the smell of an orange tree, is generated by the olfactory diffuser.

Today, there are various companies that are involved in the production of olfactory displays that emit scent, under a variety of computer control, i.e., DigiScents, Osmooze, AromaJet, TriSenx, ScentAir, Scent Collar, and so on [17, 40, 168, 184]. However, no standardized way of describing the odour has been created, and thus one smell will be represented differently depending on the manufacturer [40, 191].

Still, none of the current display devices can fully generate and transmit odour information to humans. The reasons mentioned previously limit the application of olfactory displays in virtual reality. The three problems of smell: accuracy, intensity and duration are the key areas that must be addressed for automatic smell devices to become an acceptable and widely used technology. Furthermore, as shown earlier, individuals perceive smell differently and indeed, each smell may be identified in a unique way [141]. High-fidelity smell diffusion in a virtual environment thus needs to take into account not only the airflow within the environment, but also the type of smell and the viewer him/herself [145]. However, all these new devices show that research in this field is continuing towards the development of an olfactory device that will be able to integrate well into virtual environments [36].

3.5 Multi-modal Virtual Environments

As shown earlier, our senses are constantly being stimulated by our surrounding. For example, we sense the smell of freshly made bread and we immediately turn our head in search of nearest bakery. Not only is our sense of olfaction affected but also our vision, sense of direction and balance.

All these senses can be studied individually. However, incorporating them together in a multi-modal virtual environment represents one of the goals of research in computer graphics and perception, as it has been shown to increase the user's sense of presence in virtual reality [212].

Although relationship between vision and some other senses such as audition, touch has been studied in the past [51, 111–113, 137, 154, 174, 198], very little work has been done in regard to relationship between vision and olfaction. There are various reasons for this, including a huge variety of different smells, absence of unified categorization, difficulty of on demand production [88]. Literature reports [66, 102, 130] that there are virtual environments (VEs) that include haptic feedback to provide a higher level of interaction, but only a few applications provide olfactory feedback (for example: [181]). Bafield and Danas stated that: "Olfactory information has been mainly ignored as an input to the virtual environment participant, in spite of the fact that olfactory receptors provide such a rich source of information to the human" [10]. To this day, the integration of the sense of smell has been almost exclusively a research issue.

3.5.1 Research on olfaction across different fields

Research in psychology has mainly focussed on investigating whether our sense of olfaction can aid in remembering the presented information, training, basic education, and if it enhances the virtual experience.

In 1977 Wishman et al. [194] investigated what level of odour is necessary to be present in order for it to be recognized by participants and if things such as reading a patriotic message could distract them from the odour [194]. Participants were asked to enter a laboratory for 20 seconds, and were only told that they were participating in an energy-related survey. After exiting the lab, participants were asked about the details of the room and only then, if they felt the presence of an odour. The results indicate that it took higher concentrations of smell to be recognized by a group which was diverted by a specific task (reading) than for a group of participants who just spent the time in a lab. A similar study is presented in Chapter 6.

Instead of increasing the amount of smell, we increased the amount of time spent in the test environment.

Thirty years later, Barfield and Danas analyzed the physiological and psychological aspects of olfaction in virtual environments and discussed various mechanisms of presenting odours in such an environment. Parameters such as field of smell, the great variety of smells, and spatial resolution are considered to be of great importance in such a process [10].

The 3D virtual system named “Friend Park” was developed to verify whether an incorporated sense of smell would result in the feeling of being there [183]. Participants’ questions responses such as “I feel like I was in the forest” and “I could smell the smoke of the incense”, indicate the importance of including smell into virtual environments. Nakamoto et al. created an interactive olfactory display for the cooking game [125]. They were able to control duration and strength of a certain, predefined number of smells in the cooking game. Smells are essential for reproducing reality and 90% of participants reported that smell did enhance the content’s reality. Participants reported enjoying the use of all three senses (touch, smell and sound) and some of them reported being hungry after they had tried the game. The smell of freshly cut-grass caused similar responses in the experiment presented in Chapter 5.

Mochizuki et al. developed a game called “Fragra” which incorporates olfaction and vision [118]. They created a virtual tree with various fruits, and the goal is for the user to pick the fruit and decide whether the smell released through the tube attached to his/her hand, is of the fruit picked. The number of correct answers varied with the combination of vision and smell and the general conclusion is that the visual appearance might be stronger than scent and vice versa. A few years earlier, Sarfarazi et al. showed direct evidence that odour presence affects the brain activity of visual stimulus [160].

At the Deep Immersion Virtual Environment Laboratory at the Southwest Research Institute, John Cater and his team built a backpack-mounted fire-fighter training device. The scents were delivered through a common type of fire-fighter equipment, the oxygen mask [88]. The use of smell in such an application helps in fire-fighters’ basic education and training by providing essential information about what is on fire and where. Most recently, in the project called "...towards Real Virtuality", scientists from the Universities of York and Warwick have developed a multi-modal "Virtual Cocoon", a device that is able to simulate all 5 senses [163]. The official presentation of "Virtual Cocoon" was at "Pioneers09", an EPSRC showcase event, London, March 2009.

The work done by [153] makes further progress by adding an olfactory display to virtual therapy of post-traumatic stress disorder (PTSD). PTSD is reported to be caused by "traumatic events that are outside the range of usual human experience, including (but not limited to) military combat, violent personal assault, being kidnapped or taken hostage and terrorist attack" [153]. They created a virtual environment to treat PTSD patients among Iraq War military personnel and added olfactory and tactile experiences to the environment. Simultaneous delivery of scent with visual and audio stimuli created a more realistic multi-sensory experience for the user and enhanced the sense of presence [61,153]. They also used a head-mounted display with headphones and a hand controller for movement.

The Ministry of Defence in the UK has invested £20,000 into similar research [178]. Namely, a group of researchers from the University of Birmingham is developing game-based training for, for example, soldiers being deployed to the Middle East. Smell is added in order to test its effect on training.

As has been mentioned, potential applications of olfaction in VR are numerous: games and entertainment [34,87], training [172,192], rehabilitation and therapy [153, 172], but also learning and education [181]. VR methods have gained clinical acceptance and are currently used for specific phobias, pain management, eating disorders, and post-traumatic stress disorder treatments [7, 77]. These types of VR applications could also be used for the training of medical students [168]. However, only a few such applications used in the field of education have been developed [181]. The first such application was SPIDAR (Space Interface Device for Artificial Reality) which allows students to experience "the electron bound state in the Bohr atom model, traditionally difficult for students to conceptualize" [151]. Another interesting learning application is called "Nice-smelling Interactive Multimedia Alphabet" in which three modalities were used (vision, olfaction, sound) with the goal of learning alphabet letters [151].

The need for combining research in two distinct fields such as psychology and computer graphics comes from the current inability to produce a high-fidelity rendering in real-time due to computational complexity and requirements of physically-based rendering process, which is used when the reproduction of real-world is needed.

As shown in Chapter 2, the human visual system even though a very complex structure has its own limitations. This means that there is a threshold beyond which we cannot perceive any quality improvements.

Dinh et al. created a multi-modal virtual environment composed of reception, hallway, copy room, office room and balcony [46]. They used a head-mounted display with headphones, while the smell (the scent of coffee) was delivered through "the oxygen mask connected to a canister of coffee grounds and a small pump". The sense of presence was increased with each new modality added. Although, interestingly, increasing the quality of the virtual scene, did not increase the sense of presence nor the memory of the room. However, incorporating aromas into virtual environments has been shown to be an effective memory enhancer as 95% of subjects exposed to the aroma of coffee, recalled the location of the coffee pot versus 59% of subjects from the control group.

We use these limitations to maintain the perceived quality of displayed images while reducing the time needed to render them. Mastoropoulou et al. [111–113] and Ellis et al. [51] similarly exploited these limitations in combination with audio and movement and were able to achieve significant time and cost reduction. In Chapters 4 - 7 of this thesis, we used same analogy with smell.

As shown by [212], in order to have a full experience of a virtual environment, all our senses should be stimulated. It is usually not enough to have just high-fidelity graphics. In order to increase the sense of presence. Many different techniques have been developed, one of them being perceptually based visual rendering, which uses the advantages of both top-down and bottom-up visual attention.

The exogenous (bottom-up) uses saliency maps [210], while the latter (top-down) is performed via task maps [30]. The saliency map is based on colour, intensity and orientation and is generated for each frame of the animation. Saliency maps are also used by Chalmers et al. [32] and Longhurst et al. [105]. Saliency maps modified for smell are used in Chapter 7 of this thesis.

Task maps are different from saliency maps as they use an endogenous visual attention model [30]. A task map is created from the task related objects present in the virtual scene. It is used in the rendering process in such a way that only task related elements in a scene are rendered in high quality and the remainder in low quality, without a noticeable perceptual degradation in visual quality. This has been shown to be effective in Chapter 4 as users failed to notice anything outside their task area. This rendering concept is known as "selective rendering" [41]. Selective rendering is a key part of this thesis and will be discussed in detail later.

Various user studies have shown that images can be selectively rendered without the user being aware of this difference using level-of-detail, peripheral vision, saliency and visual tasks [108,193,210]. More details can be found in the report on perceptually adaptive computer graphics by O'Sullivan et al. [131]. Cater et al., for example, showed that participants only pay attention to task related objects and ignore the rest of the scene [30]. In the experiment in question, subjects were shown two animations, one rendered in high quality (HQ) and the other in selective quality (SQ) where SQ means that only the area around the task related object was rendered at HQ and the rest at lower quality. The visual angle of the fovea was 2 degrees.

Another way of enhancing the visual rendering performance is by introducing olfactory stimuli along with the visual content as it has been reported that it adds to the realism of virtual experience [125, 178]. Using selective rendering and the limitations of human visual system it is possible to render at high quality only smell emitting objects (SEO) visible in a virtual scene, while the rest can be rendered at lower quality without perceivable degradation in virtual quality (Chapter 4). Similar experiment with audio stimuli was performed by Mastoropoulou et al. [111].

Virtual reality can allow a person to see, feel, hear and interact in a computer generated situation. However, it is far from true that all the information gathered in the real world is transmitted into the virtual. Lack of knowledge regarding the sense of smell has prevented major improvement in this area. However, even though our understanding of olfaction is far from complete, due to constant improvements in various fields, today the sense of smell is far less mysterious than it used to be [21].

Research on olfaction and its incorporation within computer graphics represent a new direction within research community, and therefore, not so much work has been carried out. However, all these findings represent a good starting point for the research presented in this thesis as they indicate the importance of smell inclusion within virtual environment. Although generating such high-fidelity virtual environments requires great computational costs and rendering times, goal of this thesis and research presented here is to show how these costs and times could be reduced and to what extent, with the help of olfaction.

Today, several institutions are working on creating multi-modal virtual environments. The integration of modalities such as vision, audition, haptics and olfaction is promising and most likely will be the “primary method of interaction in the future” [64]. Just imagine the environmental effects such as the smell of freshly cut grass and surrounding flowers as we sit in our virtual garden or “the feel of a hot summer breeze as our convertible drives through the virtual countryside” [158].

Chapter 4

Preliminary Investigation of Olfactory Influence on Perception

4.1 Introduction

Based on the findings of previous work on olfactory influence on memory, mood, and the amount of cognitive resources available to a viewer to perform a visual task, we decided to further investigate the influence of smell on visual perception, which is becoming increasingly important in computer graphics. Research on human visual perception has led to the development of perception-driven computer graphics techniques, where knowledge of the human visual system and, in particular, its weaknesses, are exploited when rendering and displaying computer generated images and virtual environments. As a first step, we will describe a study on the influence smell effects have on the perception of object quality in a rendered image.

Rendering of high-fidelity images and animations can take a long time despite the huge progress in the performance of graphics related hardware. In an attempt to achieve such high-fidelity images in a reasonable time, special techniques may be applied, which employ perceptually based criteria to speed up the computation of the rendering. This is achieved by focusing rendering quality on only those image features that are readily perceivable under certain viewing conditions, such as: on-screen distracters, for example smell- or sound-emitting object; or salient parts of a scene, for example a brightly coloured object [32, 110, 131].

This chapter presents an experimental methodology and the results of a preliminary study where we show how we can potentially accelerate the rendering of images by directing the viewer's attention towards the source of a smell and selectively rendering at high quality only the smell-emitting objects. Other parts of an image can be rendered at a lower quality without the viewer being aware of this quality difference. By doing this, we can significantly reduce rendering time without any loss in the user's perception of delivered quality. Work in this chapter has been published in [144].

4.2 Experimental Methodology

In this section the experimental methodology employed in this study is presented in detail. The hypothesis, design and equipment used, together with the participants and the procedure, will be described and discussed.

4.2.1 Hypothesis

Based on previous research findings on multi-modal perception, for example [32,112], where the authors showed that a sound emitting object (a telephone) can be used to attract human visual attention, we hypothesized that it would be similarly possible to redirect human attention towards a smell-emitting object (SEO) within a rendered scene when the smell of the object was present. Because the subject's attention would be directed to the SEO, only this part of the scene would need to be rendered in high quality. The remainder of the environment could be rendered at a much lower quality, without the viewer being aware of this quality difference, see Figure 4.1. Two conditions were considered: "Smell" and "No smell" condition. The images used in the experiment were generated using a selective renderer developed by Debattista [41], which is an extended version of the Radiance Lighting Simulation package [188]. The renderer is given a number of user-adjustable parameters: input frame to render, the default, high, rendering quality (HQ), low rendering quality (LQ) and optionally, smell-emitting object (SEO) and the size of the area (in pixels) around the SEO. In the case of presence of the SEO, the object and specified surrounding pixels are rendered at the default quality, while all the other pixels are rendered at the low quality. If no object is specified, the entire frame will be rendered using the default quality.

Figure 4.1: Our Selective Rendering approach. The smell emitting object, in this case the flowers (close up right), are rendered at a higher quality, 16 rays per pixel, while the remainder of the scene is rendered at a lower quality, 9 rays per pixel, for example the couch (close up left).

4.2.2 Participants

100 participants, of ages ranging from 19 to 30, mixed sexes, from the undergraduate and postgraduate student population of the Sarajevo School of Science and Technology (SSST) and Faculty of Electrical Engineering, University of Sarajevo (ETF), volunteered to participate in this study. All subjects reported normal or corrected-to-normal vision. None of them had any problems that might have affected their ability to smell, for example having a cold, an allergy or being pregnant. Pregnancy, even though not mentioned as an issue in previous chapter, was excluded due to possibility of smell causing a vomiting reaction or nausea. This effect could not be verified as it varies from woman to woman and therefore it was decided that

this was best left out.

The majority of the participants had attended a computer-graphics course and were thus familiar with basic concepts such as rendering quality, jagged edges as result of low quality, etc. Testing computer graphics knowledge of our participants was not the goal of this thesis or this experiment. However, knowing that they were familiar with computer graphics terms may be used to stress the importance of the results gained in this study. The subjects were randomly divided across the two conditions. The members of each of these two groups were informed that they could withdraw at any time during the experiment, however, none of them did so.

4.2.3 Design

For our experiment we used an independent-samples design. The dependent variable was the perceived relative object quality and independent variables were a) the actual quality at which the image was rendered (either high quality, low quality or selective quality) and b) the olfactory background ("smell" or "no smell").

The experiment was divided into six sessions: three sessions per each condition. During each of these conditions, subjects were shown a pair of images rendered at high quality (HQ vs HQ), high and low quality (HQ vs LQ) and high and selective quality (HQ vs SQ). For each group we used a random image order and therefore the HQ image was not always shown first. Subjects had to judge which image had the higher overall quality. If they could not distinguish between two images then they had to just choose one (forced choice). The two-alternative forced choice method is "more preferred by psychophysicists than classical yes-no task for determining thresholds, because the 2AFC procedure discourages response biases" [1, 62, 104]. Yes-no method does not take into account the "probabilistic nature of recognition" as some people are more biased towards yes (want to be agreeable, polite) while some are more biased towards no (when not sure, require more confidence) [45]. However, in 2AFC, performance is measured as a proportion of correct answers which may vary from the chance level of 0.5 (no difference between images/animations) to 1 where difference between two images/animations is perceived instantly [185]. The conditions tested are shown in Figure 4.2.

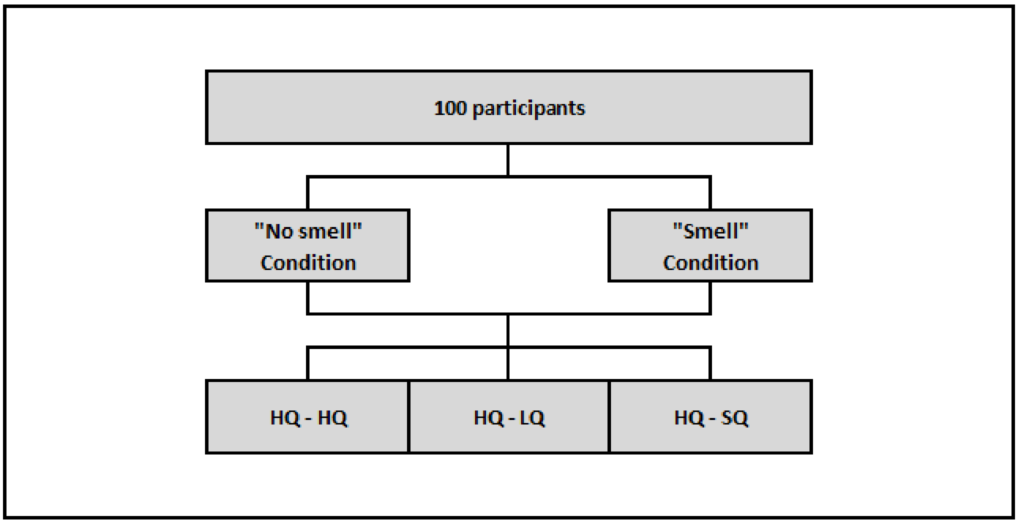

Figure 4.2: The conditions tested.

4.2.4 Equipment and Materials

The test environment comprised a PC placed on a desk in an empty room, so there were no external distractions. The subjects watched the images on full-screen on the 17" monitor of the PC (resolution: 1280×1024 pixels). No compression was applied to the images used in the experiment study in order to avoid various visual defects that might be the result of such action. The resolution chosen for all experiments in this chapter was 720×540 pixels, which was the same resolution used in similar previous research, for example [41, 111]. Pixels outside the rendered animation were shown as black. The black colour allows us to have a better contrast between image/animation and the background. Participants were seated at normal viewing distance from the monitor ($\approx 60cm$).

The scent stimulus was presented using a perfume spray. For the "smell" condition, the room was manually sprayed with perfume before subjects were let in. The smell was thus omnipresent for this experiment.

The visual stimulus used in the study was a 3D interior scene, Figure 4.3, rendered at 720×540 pixels resolution at three different qualities:

- High Quality (HQ): Entire image rendered at high quality, 16 rays per pixel (rpp), Figure 4.3. 16rpp was chosen as this quality was show to be an appropriate choice by Mastoropoulou [112].

- Selective Quality (SQ): The pixels of the SEO, i.e. the flowers, and a small surrounding area equating to the fovea angle, were rendered at high quality, 16 rpp, while the remaining pixels were rendered at the low quality of 9 rpp, Figure 4.4.

- Low Quality (LQ): Entire image rendered at low quality, 9 rays per pixel, Figure 4.5.

Figure 4.3: High quality image used in the experiment.

Figure 4.6 shows the obvious quality difference between scene details rendered at high and low quality, respectively.
For LQ we initially chose a quality setting of 1 ray per pixel but the difference was obvious to all our participants even in the SQ image so 9 rays per pixel were used instead as it represents just one quality step below 16rpp (in our scheme) but $\approx 50\%$ in computational savings. The renderer used in this study allows us to select the

Figure 4.4: Selectively rendered image.

following number of rays-per-pixel: 1, 4, 9, 16, and so on (i.e. square of real numbers 1, 2, 3, etc.). Since the difference between images rendered at 16rpp and 1rpp was obvious, we decided to test the difference between images rendered at 16rpp and 9rpp and see if any computational saving was possible. A pilot study with 20 subjects was run to determine whether a viewer would still notice the difference between an image rendered at HQ and another image entirely rendered at LQ (9rpp). The difference in visual quality was indeed still apparent to all the people who participated in this part of the experiment. The group of participants that were shown two exact same HQ images (HQ-HQ) was considered as a control group. As expected, a result of 50% (chance) for each image was achieved see Section 4.3, Table 4.3).

The third group of participants was shown two different images: one was rendered at HQ and the other one at SQ. As mentioned above, in the SQ image, the bowl with the flowers and the surrounding foveal region were rendered at high quality while the rest of the scene was rendered at low quality. The time needed to render the selective quality image was 15 minutes, while the time needed to render a full

Figure 4.5: Image rendered at low quality.

Figure 4.6: Close up of scene details rendered at high quality, 16 rays per pixel, and low quality, 9 rays per pixel respectively.

high quality image was 50 minutes. A complete list of rendering times is given in Table 4.1.

Table 4.1: Rendering times for different image qualities used in the study

Image quality	Rendering time
HQ	50min
SQ	15min
LQ(1rpp)	$\approx 3min$
LQ(9rpp)	$\approx 28min$

4.2.5 Procedure

Every experimental session lasted for approximately 1-2 minutes. During this period of time, participants were first explained what was expected from them. They were told that they will be shown two still images on a computer screen and that afterwards they will be asked questions. Each participant was tested individually and could participate in one single session. The images were shown at full screen resolution so the participant had to switch between them to be able to examine them both. As explained earlier, images were not stretched but rather shown with black background.
The question participants were asked at the end of the experiment was: "Which of the shown two images was better? To decide please consider the rendering quality".

4.3 Results

Tables 4.2, 4.3 and 4.4 show the results of the preliminary experiment. In table 4.2, 20 subjects saw the HQ image (16 rpp) and the LQ one (9 rpp). As can be seen all participants could tell the difference with and without the smell. Table 4.3 shows results of 20 participants who were shown two HQ images and a result of 50% as expected for each image was achieved. The order of shown images was random per each session.

Table 4.4 shows the results of 60 subjects who were shown the HQ image and the SQ one. 30 subjects saw the two images with no smell present, and 30 with the smell. In the "no smell" condition, the majority of participants, i.e. 80% (24 out of

Table 4.2: Results for HQ vs LQ

Conditions	Rendering quality HQ	LQ
No smell	10(100%)	0(0%)
Smell	10(100%)	0(0%)

Table 4.3: Results for HQ vs HQ

Conditions	Rendering quality HQ	HQ
No smell	5(50%)	5(50%)
Smell	5(50%)	5(50%)

Table 4.4: Results for HQ vs SQ

Conditions	Rendering quality HQ	SQ
No smell	24(80%)	6(20%)
Smell	17(57%)	13(43%)

30), correctly identified the rendered quality. On the other hand, only 57% (17 out of 30) correctly identified the HQ image in the presence of smell. This is close to the "chance" condition of 50%.

Of those who did not notice the degradation in image quality, in the "no smell" condition, 20% or 6 out of 30, this could be that the flowers are a salient feature in the image and thus likely to attract the visual attention of the viewer. As shown in Chapter 2, a number of researchers have reported that a familiar object, a most interesting object in the scene, or a salient object feature, such as colour or brightness, can indeed attract human visual attention automatically [83, 206, 209].

Even though participants were not specifically divided in terms of knowledge of computer graphics, from personal evidence we can say that those who were unfamiliar in general (about 30% of the total) had a harder time detecting differences in image quality. We consider this to be natural as they had to focus on the entire image while others (familiar with computer graphics terms), knew exactly what to look for and even possibly, where to look (i.e., object edges, shadows, and so on). Future work should explore this issue further to better understand the difference in computational savings that may be possible depending on the computer graphics knowledge of the viewer.

We used Chi-square test (χ^2) for the statistical analysis of the results since the response of subject was binary. The Chi-Square test is a non-parametric test and is commonly used to produce the statistical confidence of a hypothesis. The Chi-Square test (for 2 Independent Samples) for the unpaired comparison between the two groups gave a significant result of $p \leq 0.001$ for degrees of freedom=1, $\chi^2 = 12.258$, revealing a strong interaction between olfactory background of the selectively rendered image and perceived rendering quality. Therefore, our initial hypothesis that it would be more difficult for subjects to notice rendering quality variations in the presence of smell than while watching an image in no-smell conditions, was confirmed.

4.4 Summary

With this preliminary study we have shown that the presence of smell can indeed distract viewers from the lack of visual quality of an image. With the scent of flowers present, the subjects found it harder to distinguish the quality difference between the SQ and the HQ image, which was rendered in significantly less time (15 minutes vs 50 minutes). A rendering speedup of 333% was thus achieved in this case. These results demonstrate that the presence of a smell may indeed be exploited to speed up rendering significantly, by reducing the quality of a large portion of the rendered scene without any noticeable difference to the viewer. This work opened up a number of new avenues of research which will be discussed in the following chapters.

Chapter 5

Cross-Modal Effects of Smell on the Real-Time Rendering of Grass

5.1 Introduction

Inspired by the initial findings, we decided to investigate the cross-modal effect on the perception of the real-time animation of a field of grass in the presence of the smell of cut grass. Modeling and rendering natural scenes accurately is a major challenge for computer graphics. However, there are numerous applications which would benefit from such accurate representations of the real world such as sports' games, virtual archaeology, medical trainings and many more (see Chapter 3). Although computer-generated imagery of natural scenes has made significant progress in the last few years, for example Figure 5.1 which shows real-time rendered grass blades, the computational requirements are still high, precluding their exploitation in real-time settings on standard desktop machines.

Apart from water, grass occupies the largest area of our planet. It can be found almost everywhere. A surface of grass is composed of a large number of grass blades. When viewed from afar, grass can be simulated by a simple "green texture", but when examined close up, every blade of grass may need to be considered. In even a small field of grass this requires far too much memory and computational effort to be rendered directly [19].

Figure 5.1: Real-time rendered grass blades

Overcoming the complexity of grass in order to render it in real-time has been a challenging problem for many years. Previous approaches either render grass in real-time but with coarse approximations [9, 133, 134, 149, 164], or render grass in high quality but offline [44].

Although typically not as developed as our other senses, the presence of a pleasant or unpleasant smell can alter the way we view a scene. Such a cross-modal effect can be substantial, with parts of a scene literally going unnoticed as the smell dominates our senses. As explained in the Chapter 3, researchers believe that unpleasant odour triggers negative emotions and displeasure, as opposed to pleasant odour which can bring about positive emotions [4, 5, 155]. Rendering the high level of detail of a close-up view of a field of grass is computationally very demanding. In the real world the smell of grass would be present, and especially strong if the grass had just been cut, for example in preparation for a sports event.

This chapter outlines a study on whether the presence of a related smell could be used to reduce the level of detail in a real-time rendering application significantly without the user being aware of a reduction in quality. In particular, we investigated whether viewers would notice a reduction in the quality of the rendering of a field of grass when the smell of cut grass was present. Accurate, real-time rendering of grass has many application possibilities, especially for use in sports games.

For the purpose of this study, we used a relatively novel approach to rendering of large surfaces of grass from Boulanger [20], using dynamic lighting, dynamic shadows and anti-aliasing. This method has three levels of detail, chosen depending on the distance from the camera: geometry rendering, volume rendering with per-pixel lighting, rendering of 2D texture map with per-pixel lighting. Our approach, however, allows very detailed rendering with shadows of grass in close proximity to the viewer, and rendering of distant grass with per-pixel lighting and with a convincing parallax effect [20].

Using a level-of-detail approach provides a good compromise between lighting quality and rendering speed. Furthermore, this grass-rendering algorithm allows us to virtually render an infinite number of grass blades [19]. This work has been published in [146].

5.2 Hypothesis

We hypothesized that by exploiting the cross-modal interaction between smell and visuals we would be able to render a lower-quality version of a field of grass at a reduced computational cost, without the viewer being aware of the quality difference compared to a high-quality version. We thus considered two conditions: "No smell" and "Smell".

5.3 Participants

66 participants, ages ranging from 18 to 57, mixed sexes (19 females and 47 male) from the undergraduate and postgraduate student population of Sarajevo School of Science and Technology (SSST) and University of Warwick volunteered to participate in this study.

None of the participants reported any problem with their sense of smell, for example a cold or allergy. All of them reported normal or corrected-to-normal vision. The majority of them had taken a course in computer graphics and were familiar with concepts such as image quality and aliasing.

The participants were randomly divided in two groups across the two conditions. Members of each group were informed that they could withdraw at any point during the experiment, but none chose to do so. They were not informed about the purpose of the study.

5.4 Design

For our experiment we used an independent-samples design. The dependent variable was the relative perceived quality of a rendered animation sequence in each test pair. The independent variables were the actual quality at which animations were rendered (either high quality or low quality) and the olfactory background ("smell" or "no smell"). The conditions tested are shown in Figure 5.2.

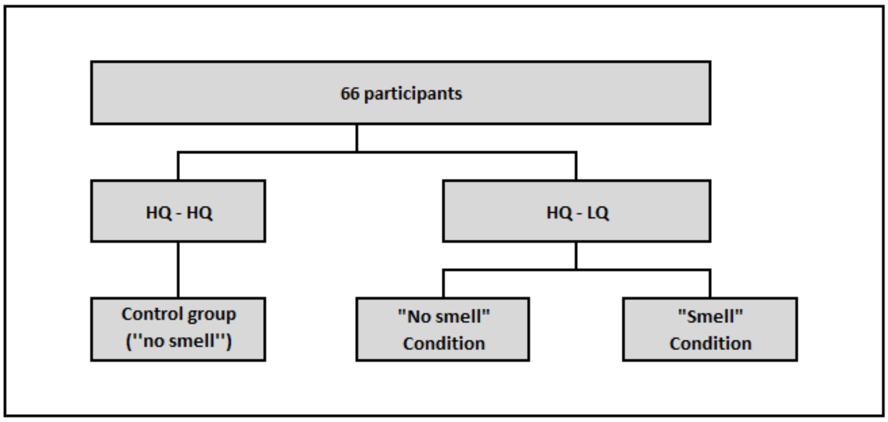

Figure 5.2: The conditions tested.

During each session, subjects watched a pair of animations that showed a flyover of a grass terrain. They viewed the animations one after the other and then had to judge which animation was of better quality. The order in which the animations were shown was random. If they could not distinguish between two shown clips, they were asked to choose one (2-Alternative Forced-Choice method, 2AFC) [1].

Both animations had the same visual content but were rendered at different qualities. The high-quality animation, HQ - Figure 5.3, was rendered with eight-times anti-aliasing for grass and with shadows. As we could manipulate only these two parameters, we choose the highest values for anti-aliasing and "yes" for shadows to represent the high quality and the opposite for low quality. Therefore, the low quality animation, LQ - Figure 5.4, was rendered with no anti-aliasing and no shadows. Both videos were rendered at 1280×800 pixel resolution using a GeForce 8600M graphic card. All settings were chosen based on previous work by co-author Boulanger [19].

The animations were recorded as fast as our hard drive could follow, which is around 2 frames per second. But, in order to have real timings, we measured the speed of the original program without recording. The rendering speed varies in this range as a function of the camera position and orientation.

- High Quality (1280×800): 6 - 7 fps
- Low Quality (1280×800): 9 - 11 fps

5.5 Equipment and Materials

The test environment comprised a PC placed on a desk in an empty room, so that the subjects would not be distracted by surrounding objects. The subjects watched animations on a full screen on a 17" monitor (resolution: 1280×1024 pixels). Animations were played at the chosen pixel resolution (1280×800 pixels) with all other pixels of the screen being black. No compression was applied to avoid any possible visual artefacts. Participants were seated at a normal viewing distance from the monitor ($\approx 60cm$).

The scent of cut grass was delivered using an off-the-shelf perfume atomizer (see Figure 5.5). This commercial atomizer releases a small puff of scent automatically at a user defined time interval. The smell was created by mixing ethanol with cis-3-hexenol in ratio 9:1. This 10% solution of cis-3-hexenol was sufficiently strong to rapidly fill the environment with the smell, even with the small volume of release of

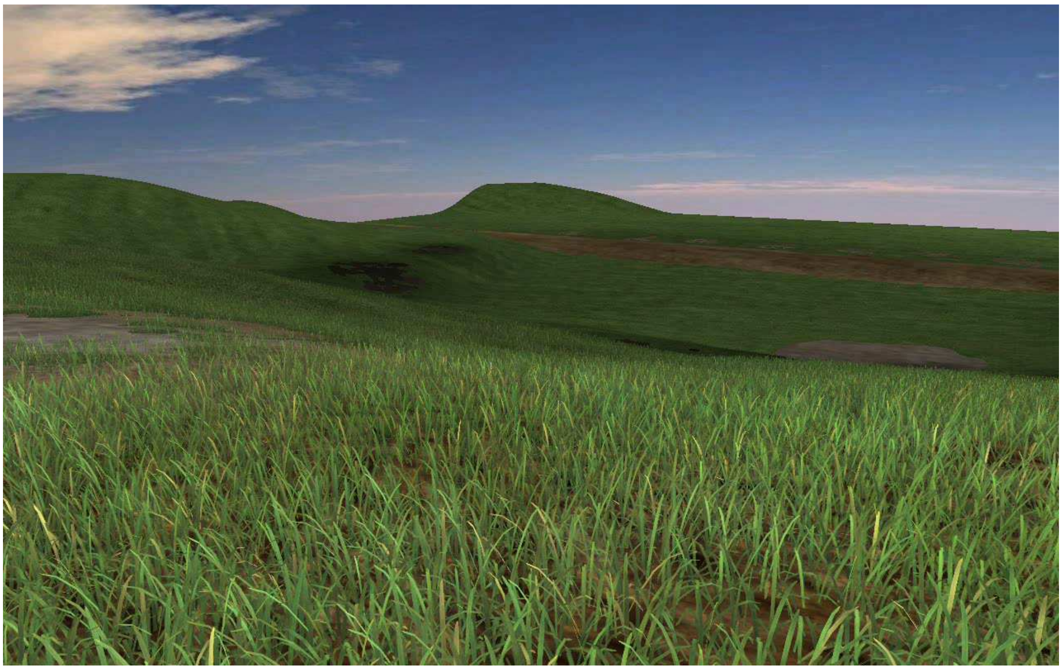

Figure 5.3: Single frame from animation sequence rendered in high quality.

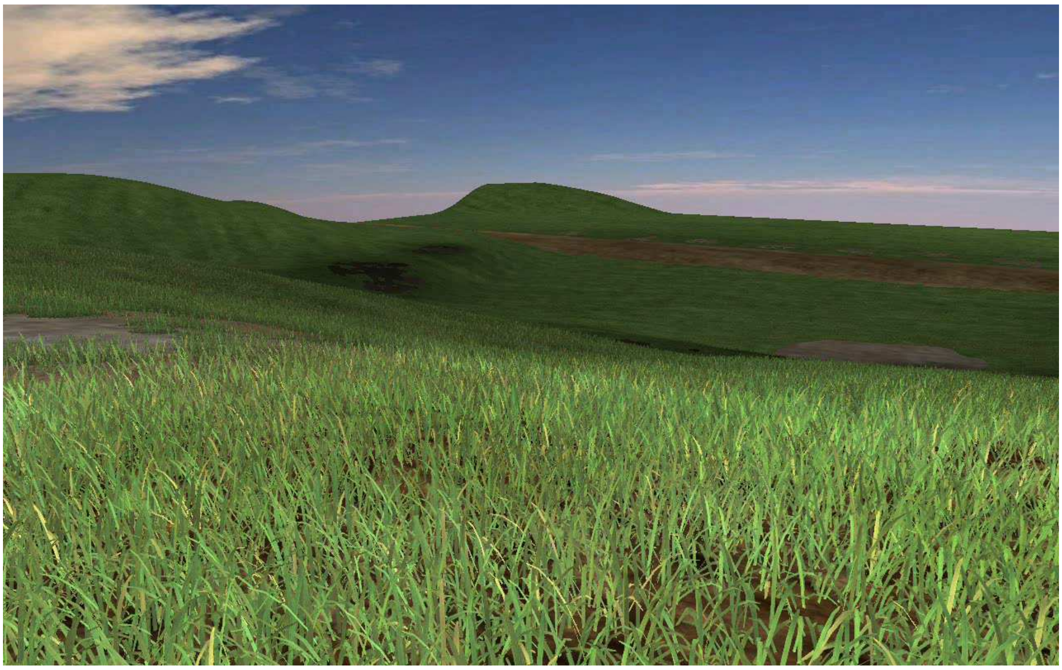

Figure 5.4: Frame from animation sequence rendered in low quality.

the odour at each “puff”.

Figure 5.5: An image of a perfume atomizer.

5.6 Procedure

Each participant individually was shown two animations, one rendered in HQ and the other rendered in LQ. The order of showing was randomized to prevent any bias. The subjects in “Smell” group were told that the animations would be accompanied by the smell of fresh cut grass which will be delivered through the use of smell delivery system. The smell is continually puffed during the experiment - so the user is receiving different concentrations over time - so will not get fully adapted and thus fail to notice the smell.

After seeing both animations, viewers were asked to answer the question: “Which of the two shown animations was of better quality taking into consideration only rendering quality?”.

Each animation was prerendered and lasted for 12 seconds. The prerendered animations were delivered to the participants at a fixed frame rate, 6-7fps for HQ and 9-11fps for LQ. This approach was chosen to ensure a consistent delivery to all participants since the actual number of frames computed and delivered directly at any point in time fluctuates depending on scene complexity.

We did not allow multiple viewings of animations as we wanted to record the first impression. Allowing multiple viewings of each animation would make it more "spot the difference in quality" task since they would be searching for a difference rather than observing an animation as a whole and then reporting which one is of better quality.

Therefore, the whole experiment took about 2 minutes for each subject as each one had to sign a consent form and anonymously supply some demographic information including details about their age, gender, eyesight, if they were having problems with smelling such as a cold or allergy, and their knowledge of computer graphics. The sample questionnaire is shown in Appendix B.

Furthermore, after having completed the experiment, each participant was asked whether the presented smell influenced their viewing experience. All participants, in this post-experiment questionnaire, felt that the presence of the smell of cut grass enhanced their viewing experience.

5.7 Results

The measure of performance in our experimental task was the percentage of times each subject correctly identified the animation rendered in high quality within the pair of displayed animations. For example, a performance of 100% within a certain condition means that all participants correctly identified the animation which was of the better quality. If the subjects could not distinguish the difference in quality, then we would expect a result of 50% as they were asked to guess if they were not sure.

A pilot study involving 6 participants was run, using the HQ animations both times.

As expected a result of 50% was achieved, meaning that 50% of our participants choose the first shown animation as the HQ one and 50% choose the second one. Results for the "No smell" condition are presented in Figure 5.6. As we can see in the figure, 80% of our participants correctly identified the high quality animation.

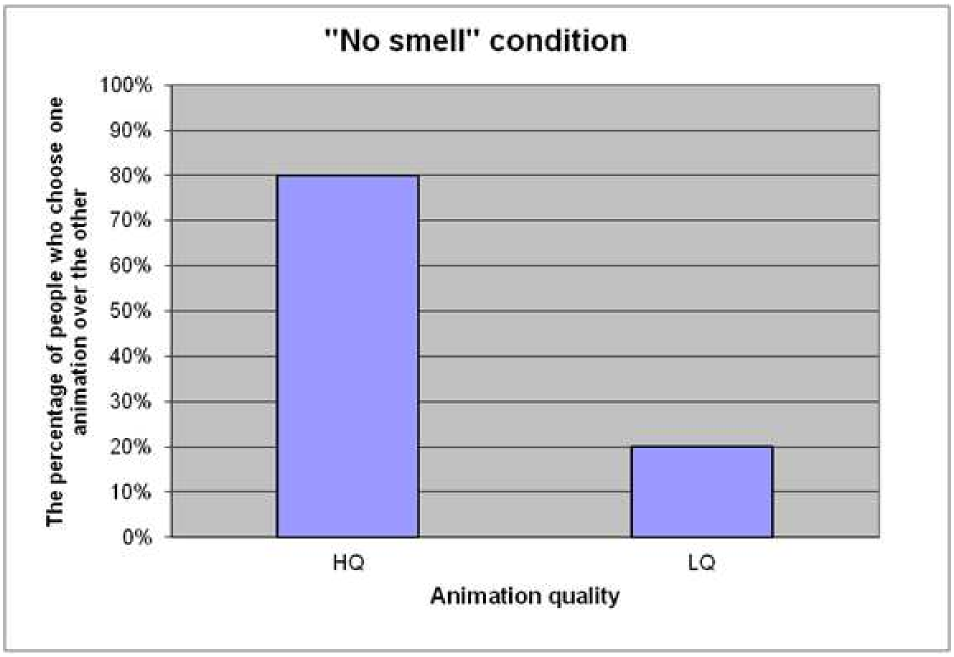

Figure 5.6: Results for "No smell" condition.

Figure 5.7 shows the results for the "Smell" condition. In this case, only 50% of the participants correctly identified the higher quality animation. Table 5.1 gives an actual number of participants who chose one animation over the other across tested conditions, while Figure 5.8 presents a comparison between two tested conditions. We created this figure to clearly show the remarkable difference in results between two tested conditions. In order to see if there is a significance in our results we used a Chi-square 2-independent samples test since we have two conditions and two different sets of subjects. For the degree of freedom 1, chi square value is $\chi^2 = 5.934$ and the level of significance is $p = 0.01$.

Therefore, the probability of rejecting the null hypothesis (noted as "smell does not have an effect on user's choice between shown high quality and low quality anima-

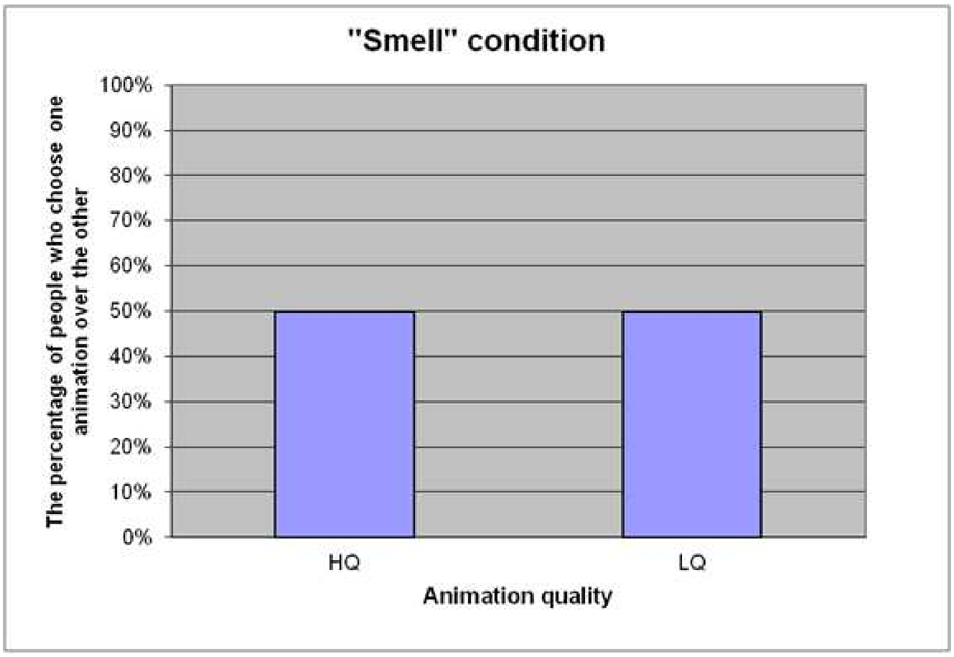

Figure 5.7: Results for "Smell" condition.

Table 5.1: Results for HQ vs LQ

Conditions	Rendering quality HQ	Rendering quality LQ
No smell	24(80%)	6(20%)
Smell	15(50%)	15(50%)

tion") when it is true (committing Type I error), in our case is equal to 1%. There is thus evidence that smell does indeed make a significant difference to a viewer's ability to distinguish the quality difference in the renderings of the field of grass. This means that by adding a related smell to a virtual environment, we can compute it for one-and-half times faster and still have an HQ effect on viewers. We consider these findings to be of great value for game developers and generally profit oriented industry as it reduces the time needed to compute and deliver potential multi-modal games, learning applications/environments and so on. However, delivering these applications interactively would require development of a framework

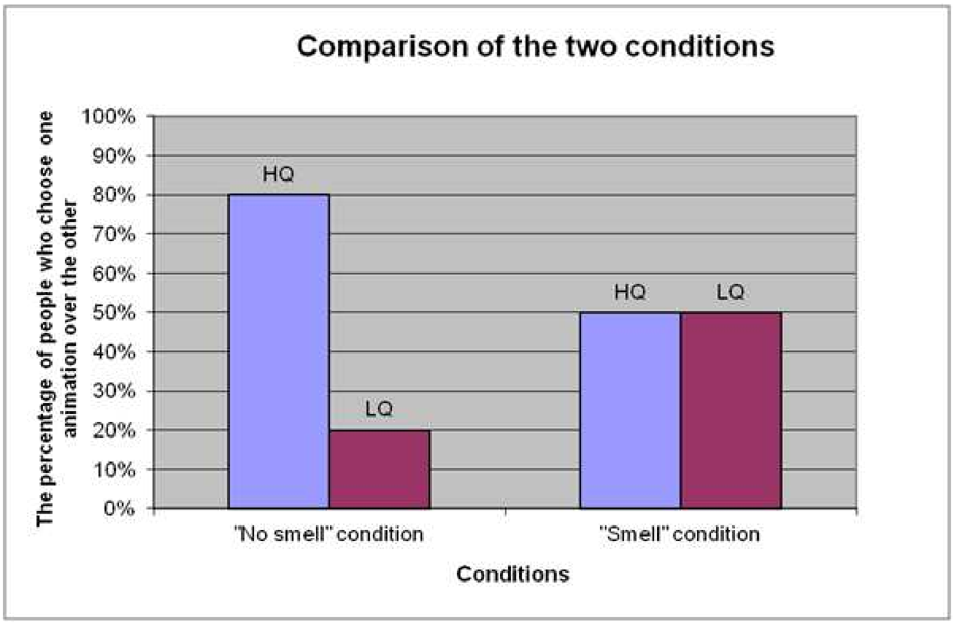

Figure 5.8: Comparison of the results for the two conditions.

which would include detailed specifications of a screenplay and therefore, detailed plan of olfactory use in a virtual environment. More specifically, the application needs to know how much of a smell can be used at a moment in time, when to use it and for how long can it be exploited to reduce the quality of an environment without perceivable difference to the user.

5.8 Summary

The results in this chapter show that the smell of fresh cut grass can indeed distract viewers from correctly identifying animation quality. Only 50% could correctly identify the HQ animation, whereas without the smell, 80% of the subjects could successfully make the distinction. We are thus able to deliver a field of cut grass at approximately one-and-a-half times the speed (9-11fps vs 6-7fps) without the viewer being aware of a quality difference. Furthermore, the smell of cut grass improved the participants' experience of the given animations, according to the post-experiment questionnaire.

Chapter 6

Adaption and Task Performance in the Presence of Smell: Its Effects on Perception of Visual Quality

6.1 Introduction

After demonstrating that smell does attract a human's attention as shown in the previous chapters (4 and 5), another important issue needs to be addressed: smell adaptation time period. Humans adapt to a smell after a period of time [96,99,141] and this needs to be considered when including smell in virtual environments. Indeed, this adaption can be a drawback as it may prevent continued exploitation of limitations of the HVS when in the presence of smell, in order to reduce overall computational time. Once adapted to smell, participants fail to notice it and thus could behave as if it was not present in the room. The human visual system is thus no longer influenced by the presence of the smell and any related computational cost reduction is no longer possible.

In this chapter a study that investigates how long it takes for an average person to adapt to the smell of lemon present in the environment is presented. Knowing the specific adaptation time interval can aid computer graphics designers in producing multi-modal virtual environments at further reduced computational costs by exploiting olfaction and its influence on human visual perception. High-fidelity virtual environments are being increasingly used as an accurate representation of the real world for a wide variety of applications, including training, phobia treatment and virtual archaeology. More details can be found in Chapter 3, section 3.5.

In addition to this, a study was performed on the influence smell has on task performance and whether smell adaptation affects this process. We used the smell of lemon as it is an example of a smell that would be instantly recognisable by both males and females. The focus of this work was not to investigate any difference in smell perception between male and female participants and therefore, throughout all studies presented here, a so called "unisex" smell was used.

6.2 Experiment - Smell Adaptation

To determine the human adaptation time interval to smell, three different conditions were performed: "no smell", "smell present throughout animations" and " smell present before the start and throughout animations" (see Figure 6.1). Two animations were used, one rendered in high quality (HQ) and the other in variable quality (VQ). The animations represent a pre-computed walk-through of a hallway model (see Figure 6.2). A complete 3D model of a long corridor and a room was created in Autodesk Maya 2009 software.

6.2.1 Design

An independent-samples design was used for the experiment where the dependent variable was the time/number of rays-per-pixel (rpp) at which participants noticed the difference and the independent variable was the olfactory background ("no smell", "smell present throughout animations" and "smell present before the start and throughout animations"). The number of rpp variable was computed based on the time variable which was reported by participants of the study and represents the time when they noticed a quality difference.

The experiment was divided in three conditions and each participant could participate in only one (between participants design). The first group watched both

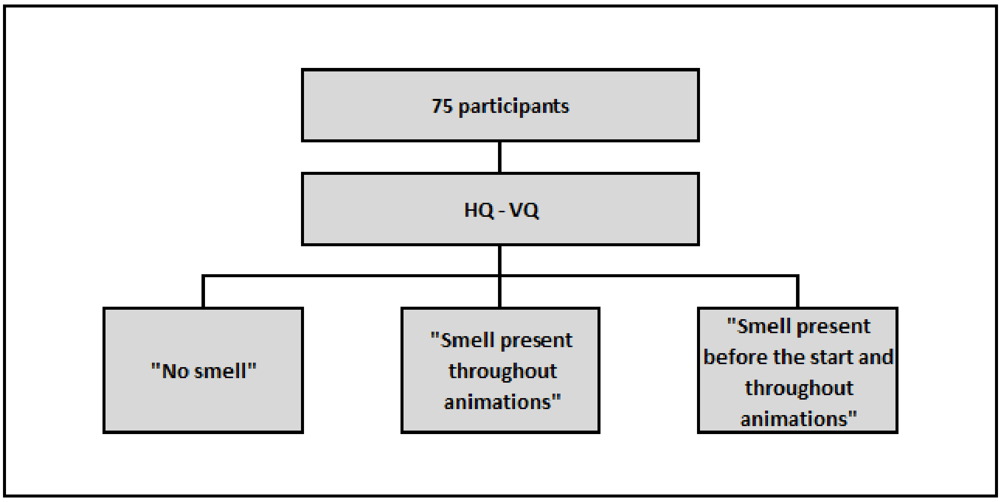

Figure 6.1: Different conditions tested in the experiment.

Figure 6.2: Single frames (940, 1770, 2200) from the HQ animation used in the experiment.

animations without smell stimuli being present in the room (condition "no smell"). The second group of participants (condition "smell present throughout animations") was asked to hold the paper which had absorbed the smell under their nose throughout watching both animations while the third group ("smell present before the start and throughout animations") were given the smell stimuli (the paper containing the absorbed smell) for a specific time period before they were shown both animations and continued to have the smell stimuli presented to them while watching animations. Details on the specific time are provided in section 6.2.5.

6.2.2 Materials

Both animations were rendered using a modified version of the Radiance *rpict* renderer [188], developed by Debattista [41]. Each animation lasted 2 minutes and was composed of 2880 frames, with a frame rate of 24 frames per second. The rendering times for each frame are given in Table 6.1. The whole experiment took about 6 minutes for each participant. Both animations had the same visual content but were rendered at different number of rpp. The HQ animation was rendered at 16rpp and VQ was rendered by decrementing the number of rpp from 16 to 1 at equal intervals (180 frames) throughout the animation (see Figure 6.3). 16rpp is used to represent HQ based on the work by Mastoropoulou et al. [112] and the results of our experiments presented in Chapters 4 and 5 [144, 146].

Table 6.1: Rendering times (per frame)

Rays-per-pixel	Rendering times
1rpp	06min 30sec
2rpp	08min 31sec
3rpp	11min 29sec
4rpp	14min 20sec
5rpp	17min 05sec
6rpp	19min 45sec
7rpp	22min 41sec
8rpp	25min 34sec
9rpp	28min 43sec
10rpp	31min 54sec
11rpp	33min 47sec
12rpp	36min 57sec
13rpp	39min 13sec
14rpp	43min 20sec
15rpp	45min 07sec
16rpp	47min 42sec

The test environment comprised a PC placed on a desk in an empty room, so that

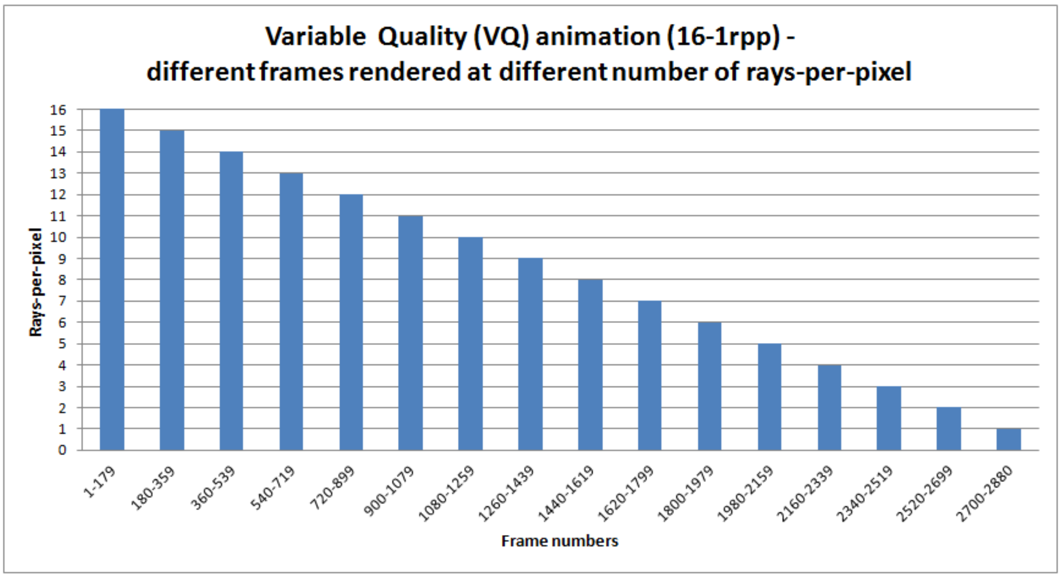

Figure 6.3: VQ animation frames rendered at different number of rays-per-pixel.

the participants would not be distracted by surrounding objects. The participants watched the animations (resolution: 720 × 576 pixels) on a full screen on a 17" monitor (resolution: 1280 × 1024 pixels). They were seated at a normal viewing distance from the monitor ($\approx 60cm$). We did not apply video compression in the study presented here and the resolution of 720×576 pixels (due to scene complexity and low system configuration settings), was used with all other pixels on the screen outside the rendered area being black.

The scent stimulus was presented using an air freshener ("DAX" - smell of lemon), which was sprayed on paper samples usually used in perfume shops for testing purposes. This was performed outside the testing environment to eliminate the possibility of having the smell present in the room before letting the participants in. As mentioned earlier, the smell of lemon was chosen as it is the most commonly used smell in households and easily recognisable by both male and female participants.

6.2.3 Participants

75 participants, ages ranging from 18 to 58, of mixed sexes (30 females and 45 male) from the undergraduate and postgraduate student population and faculty members

of Sarajevo School of Science and Technology volunteered to participate in this study. Each participant was asked to sign a consent form and complete an anonymous questionnaire including details about their age, gender, eyesight, whether they were having problems with their smell, such as a cold or allergy, and their knowledge of computer graphics (see Figure 6.4). The questionnaire is presented in Appendix C.

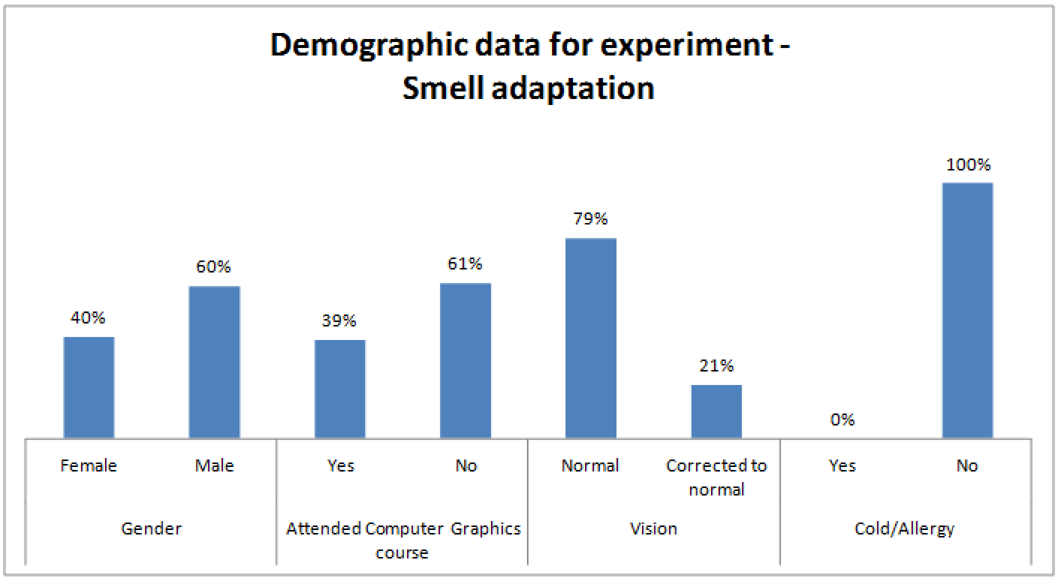

Figure 6.4: Demographic data.

6.2.4 Procedure

Prior to the start of the experiment, participants were told that they were about to watch two computer generated animations and that the first animation was rendered in high quality (HQ). They were also told that they need to stop the second animation, rendered in variable quality (VQ), once they notice the quality difference compared to the first animation (HQ). Time and number of rpp at which they noticed the difference was recorded. The members of each group were informed that they could withdraw at any time during the experiment, however, none of them choose to do so. The participants were not informed about the purpose of the experiment.

6.2.5 Results

The individual results for all three different conditions are shown in Figure 6.5 while a comparison of the results is given in Figure 6.6.

Under the “no smell” condition, participants stated they had noticed a difference between the two animations somewhere in the period from 0 seconds until 67.4 seconds. The second group of participants (condition “smell present throughout animations”) noticed the difference in quality in the period from 38 seconds until 120 seconds of the second animation rendered in VQ. The average time at which participants noticed the difference between two shown animations was: **3mins 19secs** (199 seconds = average of 38 seconds and 120 seconds plus the duration of the first animation, 2mins).

The third group (condition “smell present before the start and throughout animations”) was asked to hold the smelly paper under their noses for 199 seconds (the average time of the second group) before they were shown both animations and were asked to continue holding the paper under their noses until the end of the second animation.

The achieved results are very similar to the results of the “no smell” condition. 92% of participants identified quality difference in range from 16rpp to 8rpp compared to 100% of participants under “no smell” condition, for the same range. The similarity between these two conditions can be clearly seen in Figure 6.6.

Having the smell present for 199 seconds and then achieving almost identical results as the group of people who did not have smell present at all (“no smell” condition) suggests that the adaptation to smell time interval does indeed happen sometime after 150 seconds. The time intervals (Figures 6.5 and 6.6) represent only the range from 0 to 120 seconds of the second animation.

For the statistical analysis of these results the Kruskal-Wallis statistical test based on ranked data was used. This test was chosen as we wanted to compare non-parametric data since according to Shapiro-Wilk test, Q-Q plot and P-P plot, samples do not follow a normal distribution (see Figures 6.7, 6.8 and 6.9). The tests

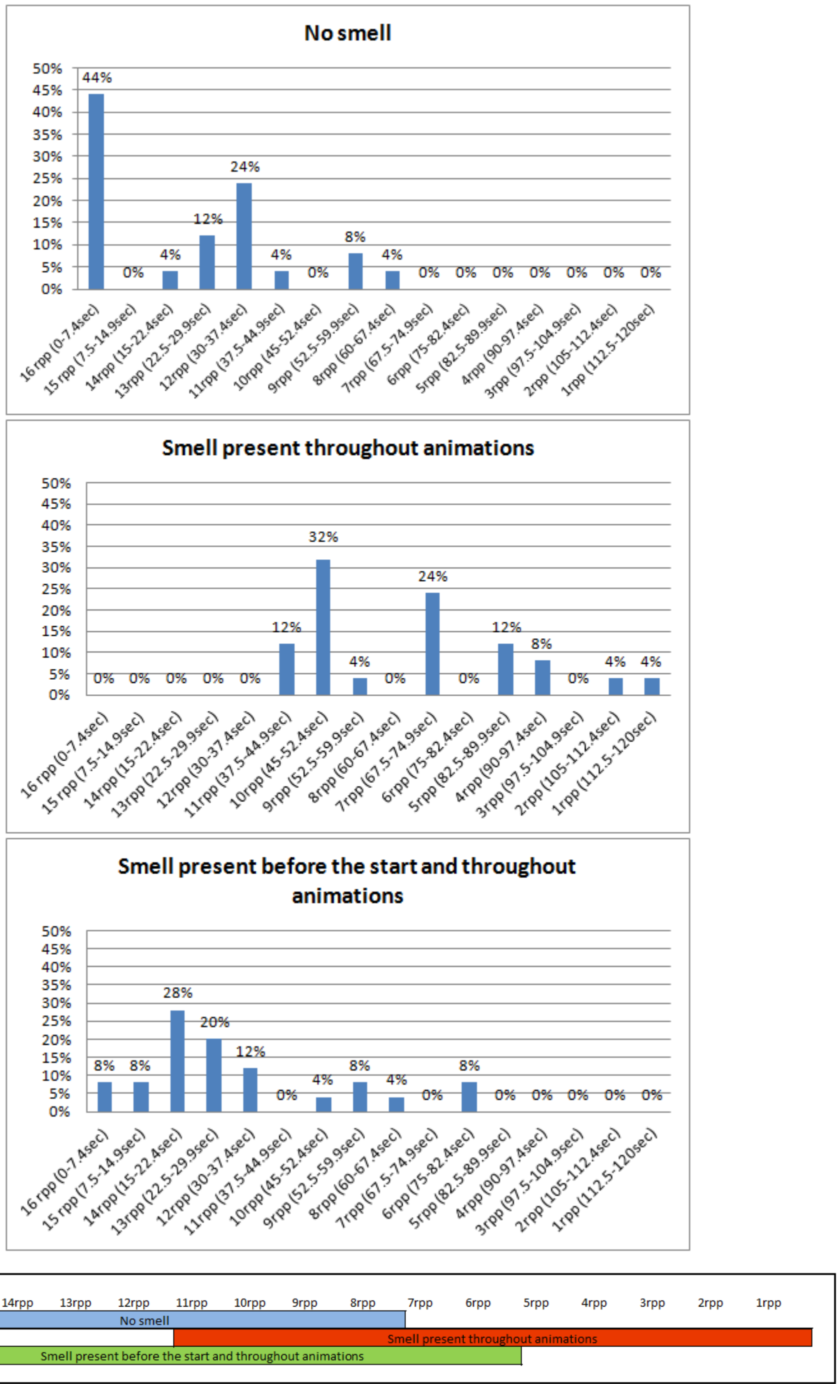

Figure 6.5: Complete results for all three conditions. The horizontal axis represents the rpp/time variable and the vertical axis the percentage of people who noticed the difference at a certain number of rpp/time interval. The lower image represents the intersection points.

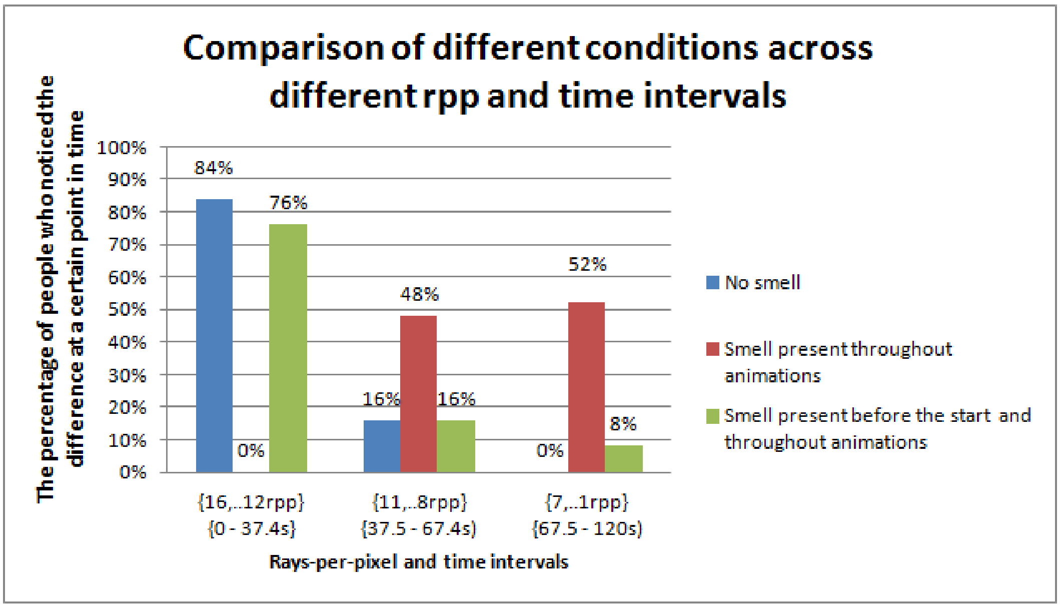

Figure 6.6: The comparison of results across different conditions and rpp/time intervals.

were performed on the number of rpp variable, i.e. the response of participants. When ranking the data, if we assume no difference between groups/conditions, then we would expect to find the summed total of ranks in each group to be about the same [58]. Similar reasoning applies when assuming the existence of difference between groups. The summed total of ranks between "no smell" and "smell present before the start and throughout animations" is 702.5 and 572.5, respectively (see Table 6.2). We assumed no difference between these two conditions. Assuming that there is a difference between "no smell" and "smell present throughout animations" conditions, the following results have been obtained: 913.5 and 361.5, respectively (see Table 6.3).

Table 6.2: Ranking of data when assuming no difference between conditions

Data (rpp)	Ranking	Conditions
6rpp	1.5	smell present before the start and throughout animations
		Continued on next page

Table 6.2 – Ranking of data when assuming no difference between conditions

Data (rpp)	Ranking	Conditions
6rpp	1.5	smell present before the start and throughout animations
8rpp	3.5	smell present before the start and throughout animations
8rpp	3.5	no smell
9rpp	6.5	smell present before the start and throughout animations
9rpp	6.5	smell present before the start and throughout animations
9rpp	6.5	no smell
9rpp	6.5	no smell
10rpp	9	smell present before the start and throughout animations
11rpp	10	no smell
12rpp	15	smell present before the start and throughout animations
12rpp	15	smell present before the start and throughout animations
12rpp	15	smell present before the start and throughout animations
12rpp	15	no smell
12rpp	15	no smell
12rpp	15	no smell
12rpp	15	no smell
12rpp	15	no smell
12rpp	15	no smell
13rpp	23.5	smell present before the start and throughout animations
13rpp	23.5	smell present before the start and throughout animations
13rpp	23.5	smell present before the start and throughout animations
13rpp	23.5	smell present before the start and throughout animations
13rpp	23.5	smell present before the start and throughout animations
13rpp	23.5	no smell
13rpp	23.5	no smell

Continued on next page

Table 6.2 – Ranking of data when assuming no difference between conditions

Data (rpp)	Ranking	Conditions
13rpp	23.5	no smell
14rpp	31.5	smell present before the start and throughout animations
14rpp	31.5	smell present before the start and throughout animations
14rpp	31.5	smell present before the start and throughout animations
14rpp	31.5	smell present before the start and throughout animations
14rpp	31.5	smell present before the start and throughout animations
14rpp	31.5	smell present before the start and throughout animations
14rpp	31.5	smell present before the start and throughout animations
14rpp	31.5	no smell
15rpp	36.5	smell present before the start and throughout animations
15rpp	36.5	smell present before the start and throughout animations
16rpp	44	smell present before the start and throughout animations
16rpp	44	smell present before the start and throughout animations
16rpp	44	no smell
16rpp	44	no smell
16rpp	44	no smell
16rpp	44	no smell
16rpp	44	no smell
16rpp	44	no smell
16rpp	44	no smell
16rpp	44	no smell
16rpp	44	no smell
16rpp	44	no smell
16rpp	44	no smell

Shapiro-Wilk test (response):

W	0.940
p-value	0.002
alpha	0.05

Test interpretation:
H0: The variable from which the sample was extracted follows a Normal distribution.
Ha: The variable from which the sample was extracted does not follow a Normal distribution.
As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.
The risk to reject the null hypothesis H0 while it is true is lower than 0.15%.

Figure 6.7: Shapiro-Wilk test summary acquired via XLSTAT add-in for Microsoft Excel.

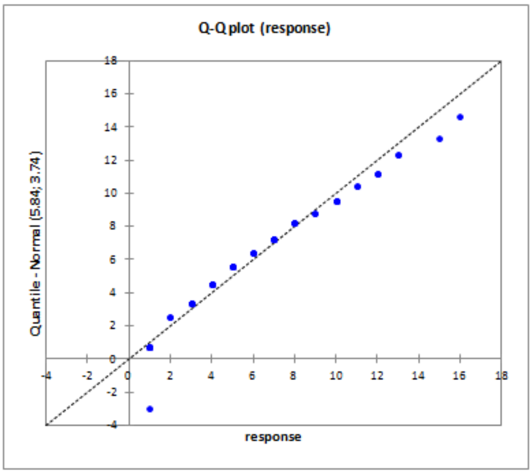

Figure 6.8: Q-Q Plot acquired via XLSTAT add-in for Microsoft Excel.

Table 6.3: Ranking of data when assuming difference between conditions

Data (rpp)	Ranking	Conditions
1rpp	1	smell present throughout animations
2rpp	2	smell present throughout animations
4rpp	3.5	smell present throughout animations
4rpp	3.5	smell present throughout animations
5rpp	6	smell present throughout animations
5rpp	6	smell present throughout animations

Continued on next page

Table 6.3 – Ranking of data when assuming difference between conditions

Data (rpp)	Ranking	Conditions
5rpp	6	smell present throughout animations
7rpp	10.5	smell present throughout animations
7rpp	10.5	smell present throughout animations
7rpp	10.5	smell present throughout animations
7rpp	10.5	smell present throughout animations
7rpp	10.5	smell present throughout animations
7rpp	10.5	smell present throughout animations
8rpp	14	no smell
9rpp	16	smell present throughout animations
9rpp	16	no smell
9rpp	16	no smell
10rpp	21.5	smell present throughout animations
10rpp	21.5	smell present throughout animations
10rpp	21.5	smell present throughout animations
10rpp	21.5	smell present throughout animations
10rpp	21.5	smell present throughout animations
10rpp	21.5	smell present throughout animations
10rpp	21.5	smell present throughout animations
10rpp	21.5	smell present throughout animations
11rpp	27.5	no smell
11rpp	27.5	smell present throughout animations
11rpp	27.5	smell present throughout animations
11rpp	27.5	smell present throughout animations
12rpp	32.5	no smell
12rpp	32.5	no smell

Continued on next page

Table 6.3 – Ranking of data when assuming difference between conditions

Data (rpp)	Ranking	Conditions
12rpp	32.5	no smell
12rpp	32.5	no smell
12rpp	32.5	no smell
12rpp	32.5	no smell
13rpp	37	no smell
13rpp	37	no smell
13rpp	37	no smell
14rpp	39	no smell
16rpp	45	no smell
16rpp	45	no smell
16rpp	45	no smell
16rpp	45	no smell
16rpp	45	no smell
16rpp	45	no smell
16rpp	45	no smell
16rpp	45	no smell
16rpp	45	no smell
16rpp	45	no smell
16rpp	45	no smell

Once the sum of ranks has been calculated, the test statistics (which has a chi-square distribution), H, is calculated. When assuming no difference and for degree of freedom=1, we have H=1.59 and p=0.2073. However, when assuming the existence of difference between two conditions, we have df=1, H=28.678 and p=0.00000009.

Therefore, from these results we can conclude that smell does significantly affect

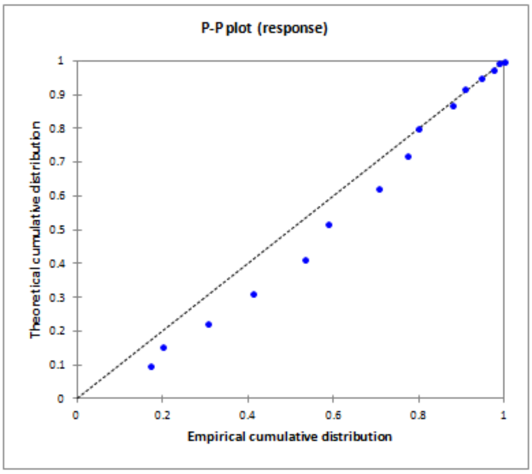

Figure 6.9: P-P Plot acquired via XLSTAT add-in for Microsoft Excel.

the perception of an environment making the participants notice the difference later than the group that was not under the influence of smell. Furthermore, the results also show that, once adapted to smell, no significant difference is found thus we can conclude the smell is no longer noticeable.

6.3 Experiment - Task Performance in the Presence of Smell

Building on the previous experiments, the affect of a task on the perception of smell was investigated. Two different conditions were tested: "no smell" and "smell" condition. For the purpose of this study we chose a simple task: counting the number of large blue balls in a shown image. As this study represents a preliminary study in this field, the goal was to see if any effect exists and for that reason a simple task was selected, rather than a more complex one.

6.3.1 Design

An independent-samples design was also used for this experiment with three dependent variables: the number of balls, whether they noticed the smell when entering the environment and when leaving. The independent variables were the olfactory conditions (“no smell” and “smell”) and the duration of time that the images were shown to participants.

The experiment was divided into twelve conditions and each participant could participate in only one (between participants design). For six groups the images were shown under the smell influence for a different period of time (15 seconds, 30 seconds, 120 seconds, 180 seconds, 240 seconds, and 300 seconds) while the other six groups watched the images under no smell presence.

6.3.2 Materials

The experiment comprised three images as shown in Figure 6.10. The time length at which the middle image was shown varied: 15 seconds, 30 seconds, 120 seconds, 180 seconds, 240 seconds, and 300 seconds. The first and last image included written instructions for the participants. Initially, we choose time slots within one minute. Based on the initial results we decided to further add additional time periods. Given the simplicity of the given task, we decided not to go above 5 minutes as all participants had concluded the task by then.

The test environment from the previous experiment was also used for this study. For the purpose of this experiment, the whole room was initially sprayed with the smell of lemon, and then additionally refreshed before each participant was allowed to enter because the smell was slowly degraded from the room due to the constant opening and closing of the doors and participants entering and leaving. This served the purpose of each participant having the same sensory experience.

6.3.3 Participants

120 participants (63 females and 57 male) from the Sarajevo School of Science and Technology volunteered to participate in this study. All participants reported having normal or corrected-to-normal vision and no cold or allergy which could have significantly affected their smelling ability (see Figure 6.11).

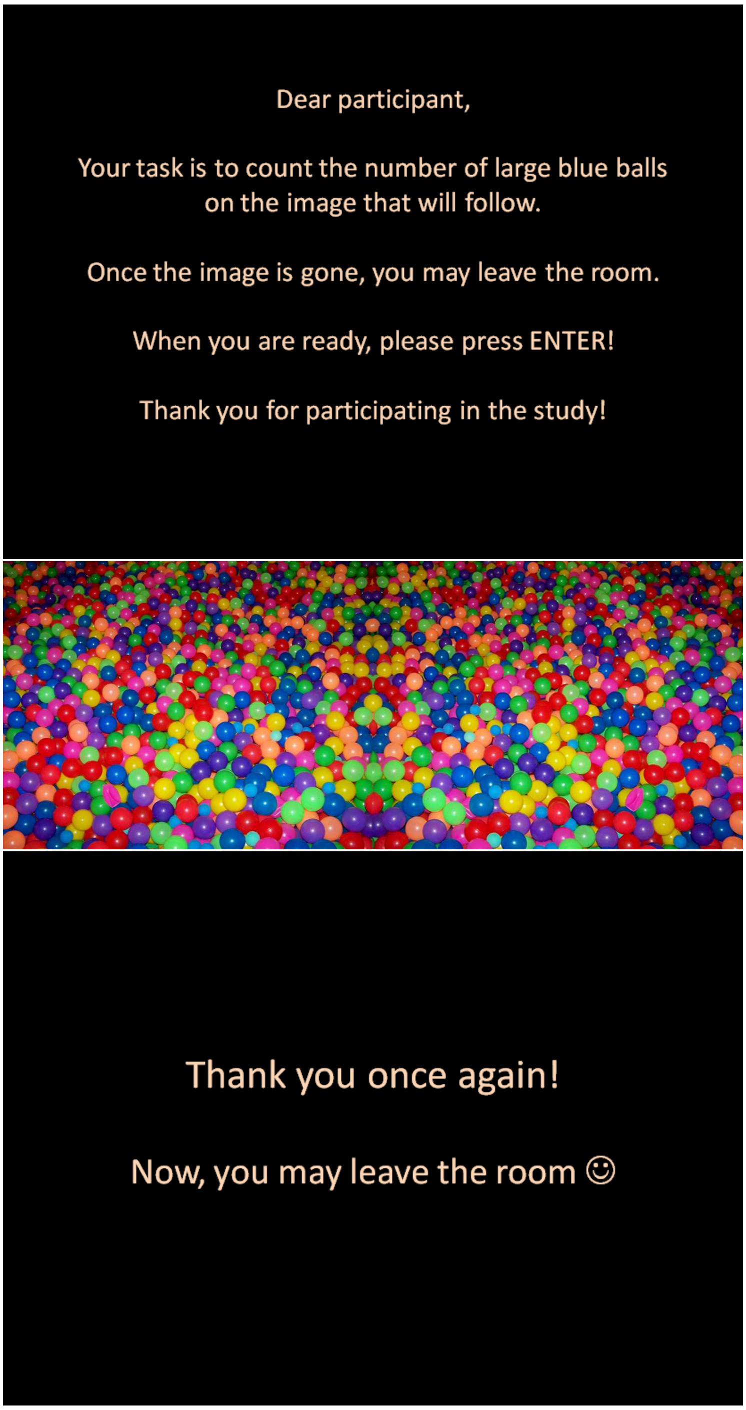

Figure 6.10: Image (middle) and instructions (top and bottom) used in the experiment.

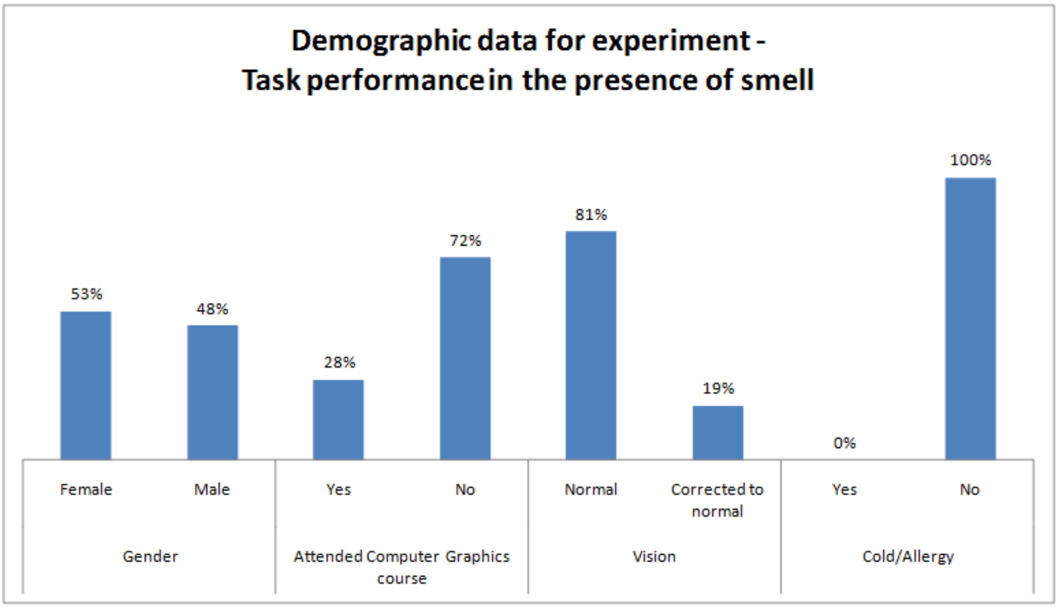

Figure 6.11: Demographic data.

6.3.4 Procedure

Prior to the start of the experiment, participants were told that they will be shown an image for a certain period of time. They were given a task: to count the number of large blue balls. When the time was up, they were instructed to leave the room. Only then, they were asked for the number they counted and if they felt the presence of smell when entering and leaving the experimental environment. The members of each group were informed that they could withdraw at any time during the experiment and they were not informed about the purpose of the experiment. None of the participants chose to leave the experimental session. The full questionnaire given to the participants at the end of this experiment can be found in Appendix D.

6.3.5 Results

The complete set of results is shown in Figure 6.12. However, analyzing the tested conditions individually (see Figures 6.13 and 6.14) we can see that for the "no smell" condition, the majority (97/120 or 80.83%) of participants reported no smell presence during all time periods when entering and when leaving the tested environment. A certain number of participants (9/60 or 15% for the question "noticed smell when entering the room?" and 11/60 or 18.33% for the question "noticed smell when leaving the room?") did not consider smell at all and reported "don't remember" while only three participants throughout (3/120 or 2.5%) reported that there was smell, when in fact none was present.

Time in seconds	Conditions tested	Did you notice any smell when you entered the experimental environment?			Did you notice any smell when you left the experimental environment?			The average percentage of the number of balls counted
		Yes	No	Don't remember	Yes	No	Don't remember	
15	No smell	10%	90%	0%	10%	90%	0%	21%
	Smell	30%	20%	50%	20%	60%	20%	18%
30	No smell	0%	70%	30%	0%	70%	30%	22%
	Smell	70%	20%	10%	30%	50%	20%	23%
120	No smell	0%	100%	0%	0%	100%	0%	41%
	Smell	70%	10%	20%	30%	40%	30%	76%
180	No smell	0%	80%	20%	0%	50%	50%	56%
	Smell	60%	40%	0%	50%	50%	0%	76%
240	No smell	0%	90%	10%	10%	90%	0%	84%
	Smell	60%	20%	20%	10%	90%	0%	92%
300	No smell	0%	70%	30%	0%	70%	30%	49%
	Smell	70%	10%	20%	0%	60%	40%	69%

Figure 6.12: The complete set of results carried out as explained in section 6.3.

However, for the smell condition, the majority of participants did notice the smell presence when entering the experimental environment (36/60 or 60%) but seemed to forget about it (reported "don't remember" or "no") when leaving (46/60 or 76.66%) (see Figures 6.12, 6.13 and 6.14). The only outlier in the above statement is the 15 seconds condition where the majority of participants (7/10 or 70%) did not remember the smell being there or said there was no smell present when they entered the room. However, when leaving the room, only 20% (2/10) of participants reported noticing smell in the room. The rest of the participants either completely ignored it (6/10 or 60% reported "no") or forgot about it (2/10 or 20% reported "don't remember").

The percentage of people who did notice the smell when leaving the room gradually grows between 15 seconds and 120 seconds from 20% to 30% while the percentage of those who said that there was no smell present gradually falls in the same time interval from 60% to 40%. The percentage of people who did not remember smell being present follows the same increase as those who reported smell presence (from

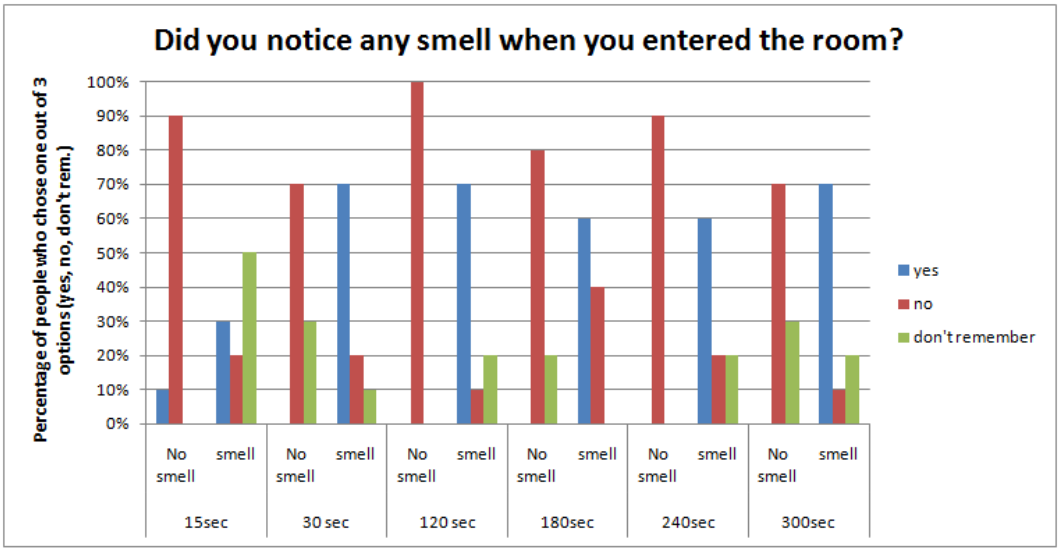

Figure 6.13: The results of the experiment for the tested conditions ("no smell" and "smell") for the question: "Did you notice any smell when you entered the experimental environment?"

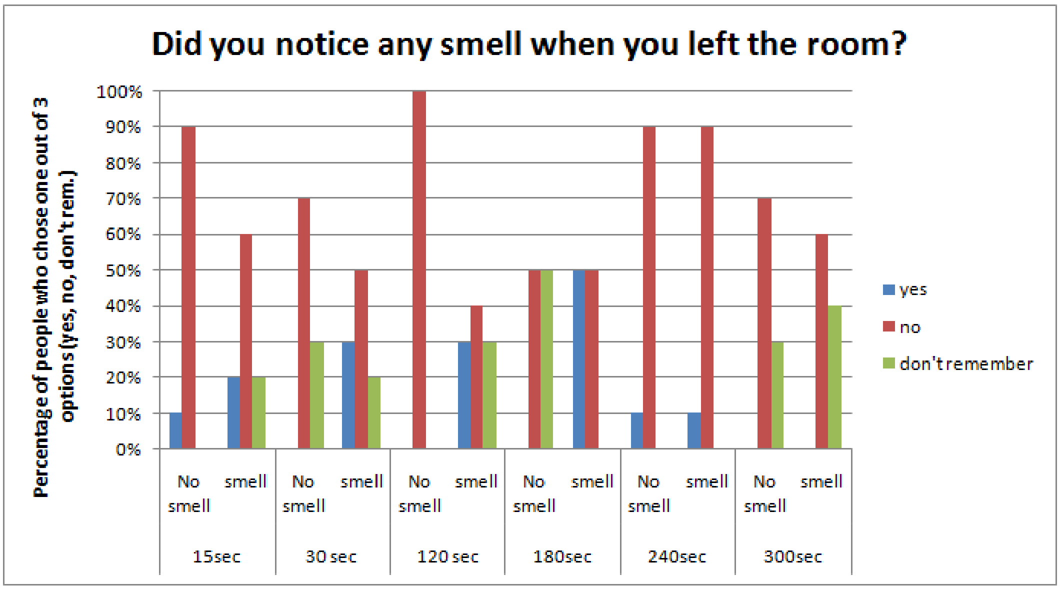

Figure 6.14: The results of the experiment for the tested conditions ("no smell" and "smell") for the question: "Did you notice any smell when you left the experimental environment?"

20% to 30%).

The 180 seconds condition represents a turning point since the same number of participants reported smell presence and absence (50:50). This condition is also interesting from the aspect of the adaptation point as it represents the adaptation-to-smell time period, according to the results of the first experiment explained earlier in this chapter, section 6.2.5. After this time slot there was a significant fall in the number of participants noticing the smell with only 10% of participants noticing the smell. Within the 300 seconds condition, the number of participants reporting that there was no smell in the room is reduced from 90% to 60%. However, the other 40% did not remember the smell presence at all. These results suggest that once adapted to smell, participants have the same perception of an environment as if there was no smell present at all (see Figure 6.14). Namely, almost identical responses were obtained to the question "Did you notice smell when leaving the room?" for both "smell" and "no smell" condition for 240 seconds and 300 seconds.

The total number of large blue balls did not vary from condition to condition. It remained constant. The average number of balls participants counted across each condition was computed. For example, 48 was the average for 15 seconds "no smell" condition, while 120 was the average for 180 seconds "no smell" condition. Instead of just showing these averages, as no easy conclusion can be drawn, we present the percentage values throughout different time slots in Figure 6.15 as it allows us to compare more easily the performance of participants (i.e. percentage of balls they counted) across different time slots. In our analysis, 100% corresponds to the total number of large blue balls present in an image that was shown to the participants. If a participant counted 92% of blue balls it further implies that he/she failed to count only 8% of them. No such straightforward conclusion can be drawn when using the actual average number counted (i.e., 48, 120, and so on).

The interesting time slot is again 15 seconds. Only here do we have a higher percentage of counted blue balls for the "no smell" condition compared to the "smell" condition. Across all other time slots, the participants counted more blue balls under the smell influence. The difference in performance between "no smell" and "smell" condition between 120 seconds and 240 seconds gradually falls from 35% (120 seconds) to 8% (240 seconds) (see Figure 6.15). Interestingly, after the 180 seconds time slot where difference was 20%, there is this significant fall, the difference being only 8%. This may imply that once adapted to smell, the performance on a given task is independent of smell meaning that once adapted, participants perform almost the same whether or not smell is present in the room.

However, we have another interesting time slot - 300 seconds, where there is a gradual fall in the ability to perform a task, since the number of balls participants counted across both conditions ("no smell" and "smell") is less than the number of balls counted in the period which is for example 2mins shorter (180 seconds). By observing participants, it appeared they over-thought a simple task when given more time. Some participants did find time to count the large blue balls more than once and gave that result as their answer, but it appeared that a second or third counting delivered less accurate results compared to the first time the balls were counted. However, the difference in performance is once again 20%. Furthermore, if we take a look at Figure 6.14, one can easily see that the 300 seconds time slot represents the only time slot during which all participants reported either the smell absence or their loss of memory of the smell presence ("don't remember" option).

6.4 Discussion

In the study presented in this chapter, the adaptation period as well as the influence of smell on the performance while doing a simple task was investigated. The investigation was done by conducting two different sets of experiments where first (adaptation) had three different conditions while the other one (task performance) two, of which each was further divided into six different time slots. Different participants were used for each of those groups (between participants design).

The results showed that human adaptation to smell happens sometime between 120 and 180 seconds (see section 6.2.5) under the conditions tested here (see section 6.2). Participants who were under the influence for this adaptation time period (condition "smell present before the start and throughout animations" - 199 seconds) ignored its presence and performed almost the same as the participants under "no smell" condition. The difference between these two is only 8% as only this percentage of participants (or 2/25) noticed the difference in quality after 67.4 seconds (i.e. below the time of "no smell" group, see Figure 6.6). All other participants (25/25 for "no

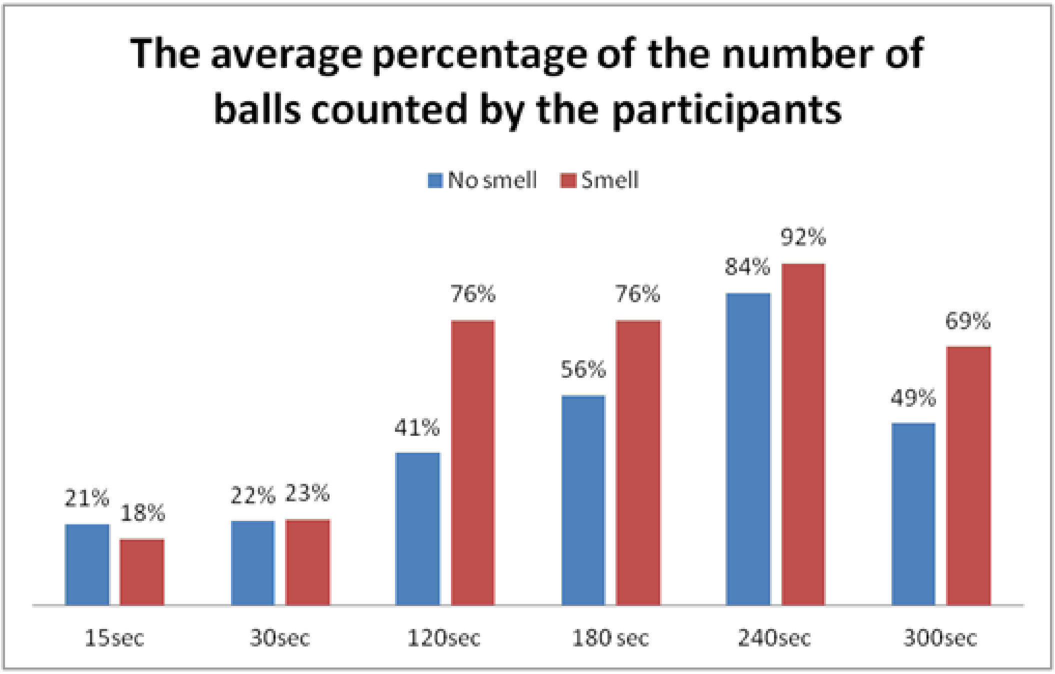

Figure 6.15: The average percentage of the number of balls participants counted during different time periods.

smell" condition and 23/25 for the "smell present before the start and throughout animations" condition) noticed the quality difference within first two intervals (i.e between 0 and 67.4 seconds).

Quality degradation without smell was related to rpp's decrease (from 16 to 1rpp) as 84% of participants were able to immediately spot the difference while watching the second animation, i.e. in period from 0 seconds to 37.4 seconds, and 0% was able to do so during "smell present throughout animations" condition (Table 6.4). The dispersion of smell was an inevitable side-effect of this experiment although once adapted to the smell, the participants should no longer notice any remaining smell on the paper.

Furthermore, when adapted to smell (third group of participants - "smell present before the start and throughout animations" condition (details on Experiment Design given in section 6.2.1)), 76% of participants noticed the difference from 0 seconds to 37.4 seconds and therefore, performed almost the same as participants who were

Table 6.4: The percentage of participants who noticed the difference at a quality of a certain number of rays-per-pixel across different conditions.

rpp	time in seconds	no smell	smell present throughout animations	smell present before the start and throughout animations
16rpp	0 - 7.4	44%	0%	8%
15rpp	7.5 - 14.9	0%	0%	8%
14rpp	15 - 22.4	4%	0%	28%
13rpp	22.5 - 29.9	12%	0%	20%
12rpp	30 - 37.4	24%	0%	12%
11rpp	37.5 - 44.9	4%	12%	0%
10rpp	45 - 52.4	0%	32%	4%
9rpp	52.5 - 59.9	8%	4%	8%
8rpp	60 - 67.4	4%	0%	4%
7rpp	67.5 - 74.9	0%	24%	0%
6rpp	75 - 82.4	0%	0%	8%
5rpp	82.5 - 89.9	0%	12%	0%
4rpp	90 - 97.4	0%	8%	0%
3rpp	97.5 - 104.9	0%	0%	0%
2rpp	105 - 112.4	0%	4%	0%
1rpp	112.5 - 120	0%	4%	0%

not under the influence of smell (84% - "no smell" condition).

After 37.4 seconds, the remaining 16% of participants noticed quality difference under "no smell" condition (up to 67.4 seconds), 100% under "smell present throughout animations" condition (up to the full 120 seconds of the animation) and the remaining 24% under " smell present before the start and throughout animations" condition (up to 82.4 seconds). Although, smell does affect perception of an environment making participants notice the quality difference much later, according to our results, this effect can be exploited for only in the region of **199 seconds** since beyond this point, participants can ignore its presence. Future work needs to investigate a more precise understanding of this point of adaptation.

A surprising result is the 44% of participants in the "no smell" condition who claimed to notice a quality difference between the two animations in the first 7.4 seconds, when in fact there was no difference (both were, at that initial stage of the animation, rendered at 16 rpp). A possible explanation for this is the inability of the participants to correctly remember the quality of the first animation. A similar result does not occur in the "smell present throughout animations" (0%) and only 8% in the "smell present before the start and throughout animations", which suggests that the participants could remember the quality between the two animations, but, importantly, could not distinguish between the two qualities. Smell is well known to improve the ability of people to remember, for example [2, 28, 37]. Future work should investigate in detail how the improvement/degradation of memory ability may be affected by the presence of smell.

Applying Kruskal-Wallis statistical test on the results, we confirmed the significant effect of smell on the perception of an environment for a specific time period making it unnoticeable after that. The results were confirmed for df=1, where we have H=1.59 and p=0.2073 when assuming no difference (conditions "no smell" and "smell present before the start and throughout animations"). However, when assuming the existence of difference between two conditions ("no smell" and "smell present throughout animations") the following results have been obtained for df=1, H=28.678 and p=0.00000009.

In the second study shown here, we wanted to see if smell affects task performance. Participants were asked to count the number of large blue balls and when exiting the experimental environment, they were asked whether there was smell present when they entered and when they left the room.

Looking at Figure 6.16, for the "no smell" condition the dominant colour across all time slots is red while blue is for the "smell" condition, meaning that majority of participants could correctly remember whether there was smell present when they entered the environment (left two images). When leaving the room, we have a similar situation for the "no smell" condition, i.e. majority of participants stated that there was no smell. Interestingly, for the "smell" condition, the dominant colour is also red, meaning that majority of participants forgot whether there was smell present when they were leaving (right two images).

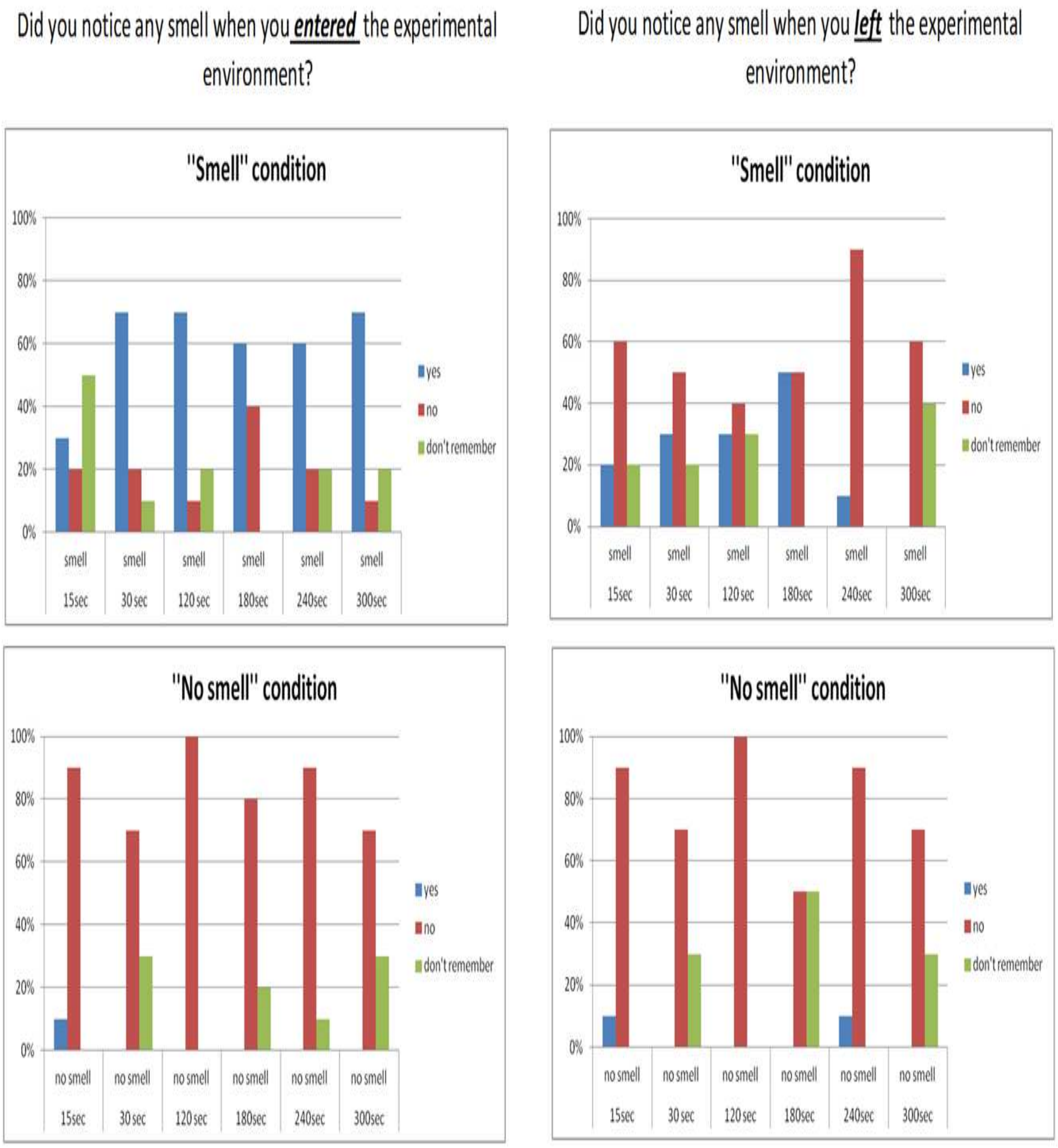

Figure 6.16: Separate view of participants responses on whether there was smell in the room at the beginning and end under "no smell" and "smell" conditions.

From the aspect of adaptation, the interesting time slot is 180 seconds (i.e. closest to adaptation time period) where we have equal number of participants stating that there was and that there was no smell in the room ("smell" condition). Below this point (240 seconds time slot) we have 90% (9/10) of participants saying that there was no smell in the room while only 10% (1/10) noticed it. As we are dealing with average adaptation time period, a possible reason for only one participant remembering smell is that he/she has not yet been adapted to smell and therefore needs more time. Future work should explore reasons for different adaptation times in more details. These could be simply related to the amount of smell initially present and whether it dissipated more quickly between different participants, or the adaptation time could be age, or gender related. If we move even further away (300 seconds), 60% of participants ignored smell and 40% did not remember. This appears to suggest that once adapted to smell and engaged in a task, participants ignore the presence of smell and behave as if it is not there. Similar responses were obtained for same time intervals under "no smell" condition (see Figure 6.16).

Furthermore, when analysing the average percentage of balls participants counted across all time slots (see Figure 6.15), in five out of six slots, participants counted better under the influence of smell. 15 seconds and 300 seconds conditions might be considered as extreme cases since they represent too little and too much time allowed for a simple task. Although, within the 300 seconds' condition, better performance was achieved under smell influence, as well.

Therefore, our results confirm the research findings of [87, 122] (Chapter 3) who reported increased performance under the introduction of smell in an environment. As seen here, participants tend to count faster when smell is present, difference reaching up to 35% (120 seconds time slot). Around the adaptation time period, the difference is smaller (20% for 180 seconds and only 8% for 240 seconds), which again is in accordance with our earlier findings (Chapter 6, section 6.3.5) where we stated that once adapted to smell, participants tend to perform almost the same as when there was no smell at all.

6.5 Summary

Our findings (see Figures 6.5 and 6.6) indicate that human adaptation to smell happens sometime after 150 seconds. All participants from the first study noticed the difference in quality in the range from 0 seconds to 240 seconds (duration of the two shown animations - 120 seconds each). Interestingly, the results show that participants behave almost the same in “no smell” and “smell present before the start and throughout animations” conditions. This further implies that, once adapted to smell, having it in the room or not, has no affect on participants.

In the second experiment, we wanted to determine the smell influence on the performance on a given task. According to the results, people count faster under smell presence. The difference in the number of balls participants counted between the two conditions (“no smell” and “smell”) is minor in the first minute (between 1% and 3%) but much greater in the later conditions. For example, the average percentage of the number of balls participants counted under the “smell” condition jumped 53% (from 23% to 76%) for period from 30 seconds to 180 seconds . Under “no smell” condition there is a rise of 34% (from 22% to 56%) and only 19% in period from 30 seconds to 120 seconds. The fall achieved under 300 seconds might be credited to the fall of interest in doing the relatively simple task, but as explained earlier (section 6.3.5), this is not the only possible explanation of this phenomenon.

Knowing the adaptation time period could significantly help in the development of multi-modal virtual environments. As our previous research has shown (Chapters 4 and 5), smell can significantly affect a users’ ability to perceive the difference between a high quality image/animation and a low quality one. Exploiting this information can help creators of such animation which include smell to reduce the rendering times and therefore the computational costs. Another important finding is that participants perform better in the presence of smell (count faster). In the case of our simple task, they counted faster compared to the participants in the “no smell” condition. However, in order to continue exploiting the non-perceivable reduction in quality of, for example, a computer game or a movie, the results indicate that a smell should be refreshed or a new smell introduced sometime after 150 seconds.

Chapter 7

Towards High-fidelity Multi-sensory Virtual Environments

7.1 Introduction

In the previous chapters smell has been shown to have a significant influence on the human visual system and perception of the environment. Also discussed were certain pitfalls of smell inclusion in virtual environments, such as smell adaptation. The final part of this thesis investigates how the presence of many different modalities such as sound, smell and ambient temperature in a virtual environment affects a viewer's ability to perceive the quality of the graphics used for that environment. For this experiment we used a number of singular and multi-sensory stimuli. This work has been published in [33, 147].

7.2 The Experiments

To investigate the cross-modal interaction between visual and other sensory stimuli, a pilot study and three experiments were conducted to see if viewers would fail to see the difference between high quality (HQ), variable quality (VQ) and low quality (LQ) animations. The viewers were presented with a walk through of a hallway model in the presence of olfaction, temperature and/or audio noise stimuli. The animation comprised 240 frames.

7.2.1 Design

An independent samples design was used for all the experiments. The dependent variable was the perceived relative quality of a rendered animation sequence in each test pair. The independent variables were the actual quality at which the animations were rendered (either HQ, VQ or LQ) and the background (smell, temperature and/or noise). The order of the animations shown was randomized. A 2-Alternative Forced Choice (2AFC) method was used [1].

7.2.2 Materials

All animations were rendered on an Intel Celeron computer working on 1.60GHz. The rendering times for each of the animations (240 frames) are given in Table 7.1, with example images of the same frame at different quality shown in Figure 7.1. The sub-linear growth of the computation time is due to the use of an irradiance cache for which the computation time is sub-linear with resolution [189].

The test environment comprised a PC placed on a desk in an empty room, so that the participants would not be distracted by surrounding objects. As in previous experiment (Chapter 6), the participants watched the animations using a resolution of 720×576 pixels on a 17" monitor (resolution: 1280×1024 pixels). Pixels outside the rendered area were shown as black. They were seated at a normal viewing distance from the monitor ($\approx 60cm$).

The scent stimulus was presented using a perfume spray. For the strong perfume condition, the room was initially sprayed with 6ml of Lacoste “Pink” perfume (ingredients: orange, coriander leaves, cardamon seed, jasmine, violet leaves, carrot-seed oil, drop of vanilla) and later on an additional 6ml was sprayed as participants entered the room. This perfume was chosen after a pilot study showed that the scent was clearly discernible above any possible ambient smells in the room. Furthermore, the scent was “pleasant” minimizing any negative reactions by the subjects to the smell.

Table 7.1: Rendering times (per frame)

Rays-per-pixel	Rendering times
1rpp	06min 30sec
2rpp	08min 31sec
3rpp	11min 29sec
4rpp	14min 20sec
5rpp	17min 05sec
6rpp	19min 45sec
7rpp	22min 41sec
8rpp	25min 34sec
9rpp	28min 43sec
10rpp	31min 54sec
11rpp	33min 47sec
12rpp	36min 57sec
13rpp	39min 13sec
14rpp	43min 20sec
15rpp	45min 07sec
16rpp	47min 42sec

For the mild perfume condition, the room was left closed and the experiment was done the day after the "strong perfume" group finished. The presence of smell was not as strong as the day before but it still could be sensed in the room. Participants' immediate identification of smell was considered as a "strong" condition and similarly their failure to notice a smell immediately was considered as a "mild" condition. This does not mean that for some participants "mild" condition was in fact "strong" condition and vice versa because these two conditions were done on different days with different participants. However, all participants in "strong" condition noticed the smell immediately when entering the experimental area which was not the case with participants in the "mild" condition.

The high-temperature condition was achieved using a heater in the room. The temperature was in the range 25-30° Celsius. A high-temperature condition was chosen

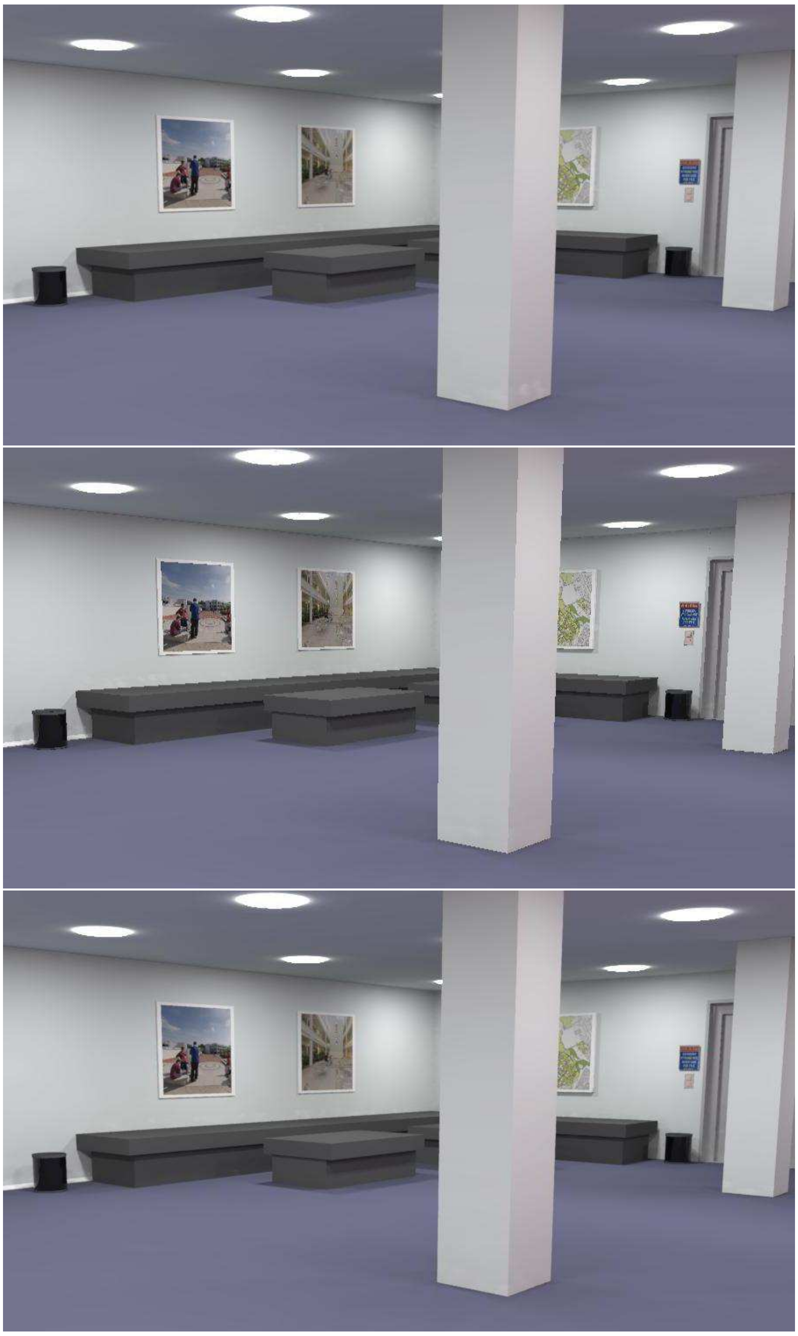

Figure 7.1: Single frame(125) rendered at HQ - 16rpp (top), LQ - 1rpp (middle) and VQ - 5rpp (bottom).

rather than a normal or cold temperature as a pilot study had shown only the high temperature had an effect on participants. For the sound part of the experiment, noise (pink) was used as it had previously been shown to give significant results [79]. These are the general materials used in the experiments, while the specific ones (i.e. the animations) are discussed in the specific sections. The experimental methodology employed in the pilot study for individual modalities (smell and temperature) is also elaborated on in the following sections.

7.2.3 Procedure

Each animation lasted 10 seconds and was composed of 240 frames with a frame rate of 24 frames per second. The whole experiment took about 2 minutes for each participant. Each participant was asked to sign a consent form and complete an anonymous questionnaire including details about their age, gender, eyesight, if they were having problems with smelling such as a cold or allergy, and their knowledge of computer graphics (Figure 7.2; see Appendix A and B). After viewing both animations, participants were asked to answer the question: "Which of the two shown animations was of better quality taking into consideration only rendering quality?". They were also asked to explain and show why they thought one was of better quality than the other. The members of each group were informed that they could withdraw at any time during the experiment. The participants were not informed about the purpose of the experiment.

7.2.4 The Pilot Study

In the pilot study the perceived visual quality was tested for each stimulus independently. Four different sets of high-fidelity images were used: Checkerboard, Corridor, Kalabsha and Library (see Figure 7.3), rendered at 1, 4, 9, 16, 25, 36 or 49 rpp. The sampling was stratified using a square grid. The work by Hulusic et al. [79] showed that 49 rpp represents a suitable gold-standard image beyond which there was no significant perceived difference between images. Table 7.2 shows the different rendering times. The experiment was done using a timed power point presentation. Each condition consisted of 28 pairs of images, where each image pair was composed of a gold standard image (image rendered at 49rpp) and another image rendered at

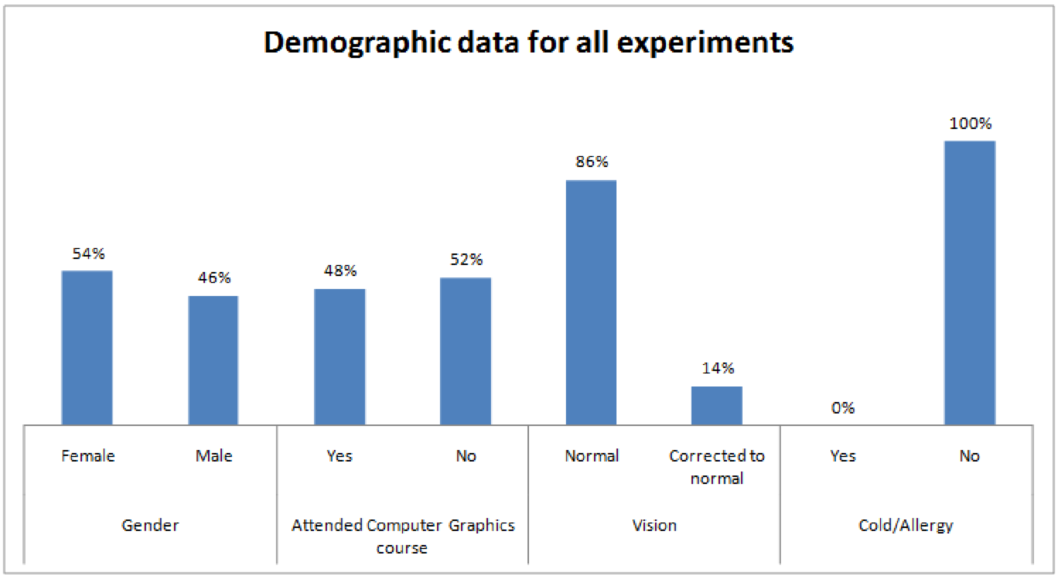

Figure 7.2: Demographic data.

lower number of rpp. The images were shown one after the other in a five-slide sequence, where each image lasted for 5 seconds, and letters “A”, “B” and the sign “?” for 1 second (see Figure 7.4). All image pairs were ordered randomly to avoid any bias. In a psychological study by Peterson and Peterson, it was demonstrated that humans have a hard time remembering even three elements for more than eighteen seconds in the presence of distracters [135]. Therefore, each image pair lasted for thirteen seconds, which is less than the remembering time threshold and the whole experiment lasted for approximately six minutes. The experiment was performed in an empty room to reduce external distractions. The participants were seated at a normal viewing distance from the monitor ($\approx 60cm$).

7.2.4.1 The Smell

In this study, for the pleasant smell Lacoste “Pink” perfume was chosen. The procedure of using the smell is explained in section 7.2.2.

Three different conditions were used in the experiment: “no smell”, “strong perfume” and “mild perfume”. 66 participants (22 per each condition), of ages ranking from 16 to 40, mixed sexes, from the undergraduate and postgraduate student pop-

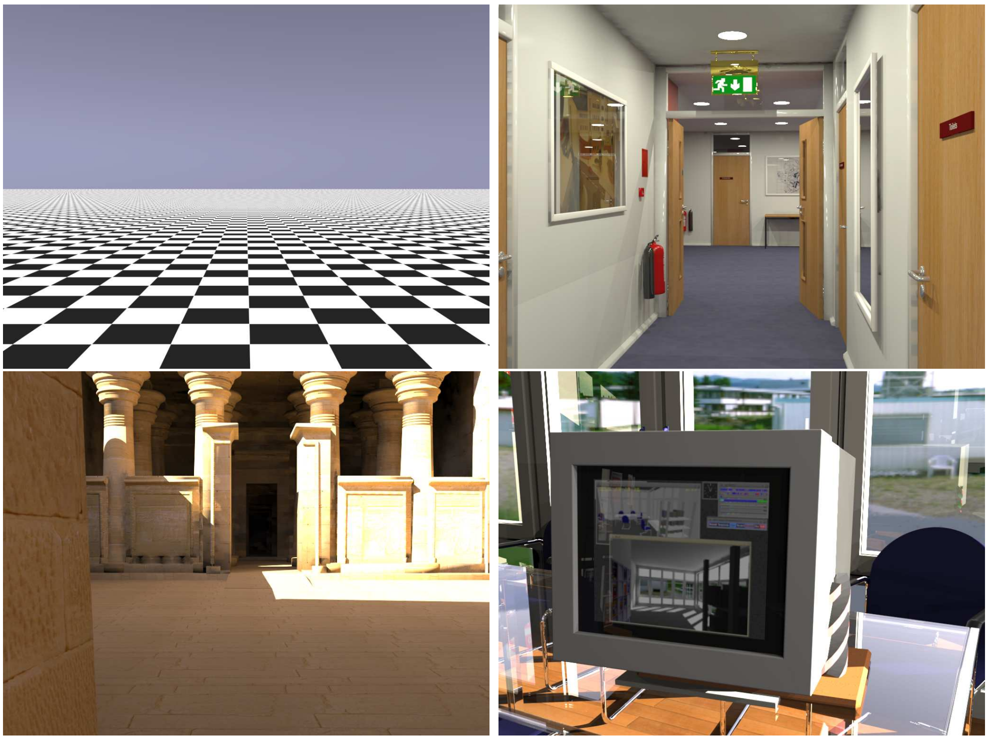

Figure 7.3: Images used in the experiment: Checkerboard (top left), Corridor (top right), Kalabsha (bottom left), Library (bottom right).

Table 7.2: The rendering times for all scenes presented in seconds

Rays-per-pixel	Checkerboard	Corridor	Kalabsha	Library
1rpp	13.12	673.99	98.29	130.57
4rpp	51.98	1431.31	170.00	513.40
9rpp	115.81	2471.16	288.62	1153.65
16rpp	206.89	4110.91	409.61	2086.31
25rpp	329.79	5556.64	581.24	3354.27
36rpp	464.08	7807.02	796.40	4627.24
49rpp	812.92	10327.32	1057.14	6277.47

ulation of the SSST (Sarajevo School of Science and Technology), volunteered to participate in this study. The participants were asked to identify which image was of better quality in the shown pair of images. The test pairs were: 1v49, 4v49, 9v49,

Figure 7.4: The example of five-slide sequence used in the experiment.

16v49, 25v49, 36v49 and 49v49 (more details in section 7.2.4). If they could not distinguish between two images then they had to just choose one (forced choice). They were randomly divided across different conditions. The results are presented in two forms, the real experimental data which shows what percentage of participants choose one or the other image in an image pair under different conditions (see Figure 7.5) and the statistically analyzed data where significant results are written in bold (see Tables 7.3 to 7.5).

A Chi-square analysis was performed on the two variables, "actual quality" and "perceived quality" of the rendered images, separately across all scenes and conditions. The analysis compared participants' responses for various image pairs shown per condition. The null hypothesis for each pair of images was that they should have equal preference. Computed Chi-square values are given in Tables 7.3 to 7.5 for each scene, divided across different conditions. According to these results, participants failed to see the difference amongst the shown images with the increase in the number of rays-per-pixel in majority of cases. The results indicate that the difference in quality was mostly obvious between images rendered at 1 (across all scenes), 4 (Checkerboard and Library scenes), 9 (Library scene) and 16 (Corridor and Library scenes) rpp. For these numbers of rays-per-pixel, chi-square analysis revealed overall significant result only for the "strong perfume" condition for $p \leq 0.05$. For this condition, the average of Chi-square values for images rendered at 1, 4, 9 and 16 rpp is $\chi^2 = 4.26$ and the level of significance is $p = 0.039$. The average of Chi-square values for "mild perfume" condition is $\chi^2 = 2.40$ and the level of significance is $p = 0.121$. In the further experimental study it was decided to take into additional consideration these two conditions in order to see if the strength of a smell together with other modalities such as sound and temperature could be used to distract viewer and make them perceive a LQ or VQ animation as an HQ one.

Scene	Rpp at which images were rendered (first-second)	No smell		Strong perfume		Mild perfume	
		First	Second	First	Second	First	Second
Checker board	49-1	77%	23%	77%	23%	50%	50%
	49-4	68%	32%	73%	27%	73%	27%
	49-9	64%	36%	68%	32%	41%	59%
	49-16	68%	32%	50%	50%	36%	64%
	49-25	55%	45%	50%	50%	41%	59%
	49-36	59%	41%	64%	36%	64%	36%
	49-49	55%	45%	64%	36%	50%	50%
Corridor	49-1	50%	50%	77%	23%	55%	45%
	49-4	68%	32%	55%	45%	68%	32%
	49-9	50%	50%	41%	59%	41%	59%
	49-16	41%	59%	55%	45%	23%	77%
	49-25	55%	45%	64%	36%	36%	64%
	49-36	59%	41%	45%	55%	50%	50%
	49-49	45%	55%	68%	32%	45%	55%
Kalabsha	49-1	73%	27%	77%	23%	73%	27%
	49-4	68%	32%	68%	32%	59%	41%
	49-9	59%	41%	59%	41%	59%	41%
	49-16	55%	45%	64%	36%	36%	64%
	49-25	68%	32%	55%	45%	50%	50%
	49-36	55%	45%	45%	55%	64%	36%
	49-49	45%	55%	45%	55%	55%	45%
Library	49-1	86%	14%	91%	9%	68%	32%
	49-4	73%	27%	91%	9%	82%	18%
	49-9	73%	27%	59%	41%	36%	64%
	49-16	55%	45%	73%	27%	50%	50%
	49-25	36%	64%	45%	55%	55%	45%
	49-36	50%	50%	59%	41%	41%	59%
	49-49	50%	50%	73%	27%	41%	59%

Figure 7.5: The results of pilot study.

7.2.4.2 The Ambient Temperature

57 participants of which 19 were females and 38 were males, from the undergraduate student population of the Faculty of Electrical Engineering, Sarajevo volunteered to participate in this study. The participants were divided across three different conditions: "low temperature", "normal temperature" and "high temperature". Three ambient temperature levels were chosen for the test room temperature: 10-14°, 20-24°, 25-30° Celsius which corresponds to low, normal and high ambient temperature labels respectively. The air temperatures were manipulated using the existing mechanical ventilation system in the two experiments. For the first condition labelled as "low temperature", the average temperature when the air was cooled was 12° Celsius, and the average temperature in the second condition "normal temperature", was 22° Celsius. For the "high temperature" condition the heater was adjustable to

Table 7.3: "No smell" condition. Chi-Square Analysis (df=1; critical value 3.841 at 0.05 level of significance). Significant results are written in bold.

	Checkerboard		Corridor		Kalabsha		Library	
rpp	χ^2	p	χ^2	p	χ^2	p	χ^2	p
1	**6.55**	**0.01**	0.00	1.00	**4.55**	**0.03**	**11.64**	**0.00**
4	2.91	0.09	2.91	0.09	2.91	0.09	**4.55**	**0.03**
9	1.64	0.20	0.00	1.00	0.73	0.39	**4.55**	**0.03**
16	2.91	0.09	0.73	0.39	0.18	0.67	0.18	0.67
25	0.18	0.67	0.18	0.67	2.91	0.09	1.64	0.20
36	0.73	0.39	0.73	0.39	0.18	0.67	0.00	1.00
49	0.18	0.67	0.18	0.67	0.18	0.67	0.00	1.00

Table 7.4: "Strong perfume" condition. Chi-Square Analysis (df=1; critical value 3.841 at 0.05 level of significance). Significant results are written in bold.

	Checkerboard		Corridor		Kalabsha		Library	
rpp	χ^2	p	χ^2	p	χ^2	p	χ^2	p
1	**6.55**	**0.01**	**6.55**	**0.01**	**6.55**	**0.01**	**14.73**	**0.00**
4	**4.55**	**0.03**	0.18	0.67	2.91	0.09	**14.73**	**0.00**
9	2.91	0.09	0.73	0.39	0.73	0.39	0.73	0.39
16	0.00	1.00	0.18	0.67	1.64	0.20	**4.55**	**0.03**
25	0.00	1.00	1.64	0.20	0.18	0.67	0.18	0.67
36	1.64	0.20	0.18	0.67	0.18	0.67	0.73	0.39
49	1.64	0.20	2.91	0.09	0.18	0.67	**4.55**	**0.03**

achieve any temperature between 25 and 30 ° Celsius.

Similar to the previously described experiments, this experiment also showed that the greater the number of rays per pixels is, the less perceivable difference was obtained, as was expected. The greatest difference was observed between images rendered at 1, 4, 9 and 16 rpp.

The average results of the Chi-square values across each of the three conditions ("normal temperature", "high temperature" and "low temperature"), show that in-

Table 7.5: "Mild perfume" condition. Chi-Square Analysis (df=1; critical value 3.841 at 0.05 level of significance). Significant results are written in bold.

	Checkerboard		Corridor		Kalabsha		Library	
rpp	χ^2	p	χ^2	p	χ^2	p	χ^2	p
1	0.00	1.00	0.18	0.67	**4.55**	**0.03**	2.91	0.09
4	**4.55**	**0.03**	2.91	0.09	0.73	0.39	**8.91**	**0.00**
9	0.73	0.39	0.73	0.39	0.73	0.39	1.64	0.20
16	1.64	0.20	**6.55**	**0.01**	1.64	0.20	0.00	1.00
25	0.73	0.39	1.64	0.20	0.00	1.00	0.18	0.67
36	1.64	0.20	0.00	1.00	1.64	0.20	0.73	0.39
49	0.00	1.00	0.18	0.67	0.18	0.67	0.73	0.39

creased air temperature reduces the participants perceptual differentiation ability. On the other hand, the results for the "low temperature" condition improve the performance of the participants meaning that they were able to correctly identify the image quality. The average of Chi-square values for images rendered at 1, 4, 9 and 16 rpp for "high temperature" condition is $\chi^2 = 1.71$ and the level of significance is $p = 0.190$. This study was performed by our colleague Aida Sadžak from the Faculty of Electrical Engineering, University of Sarajevo, and the results are in the process of being published.

7.2.5 Experiment 1

This experiment was run to begin to understand the effect, due to the large number of modalities that will be present in high-fidelity multi-sensory virtual environments. This study focuses only on how the different modalities affect the visual component of rendering computed with physically-based lighting. Figure 7.6 shows all the conditions tested in this experiment.

All animations had the same visual content but were rendered at a different number of rays-per-pixel(rpp). The HQ animation was rendered at 16rpp (Figure 7.7), LQ at 1rpp and VQ was rendered by decrementing the number of rays from 16 to 1rpp at equal intervals (15 frames) throughout the animation. Figure 7.8 shows a close-up view of the differences between HQ, LQ and VQ images. 16rpp was chosen

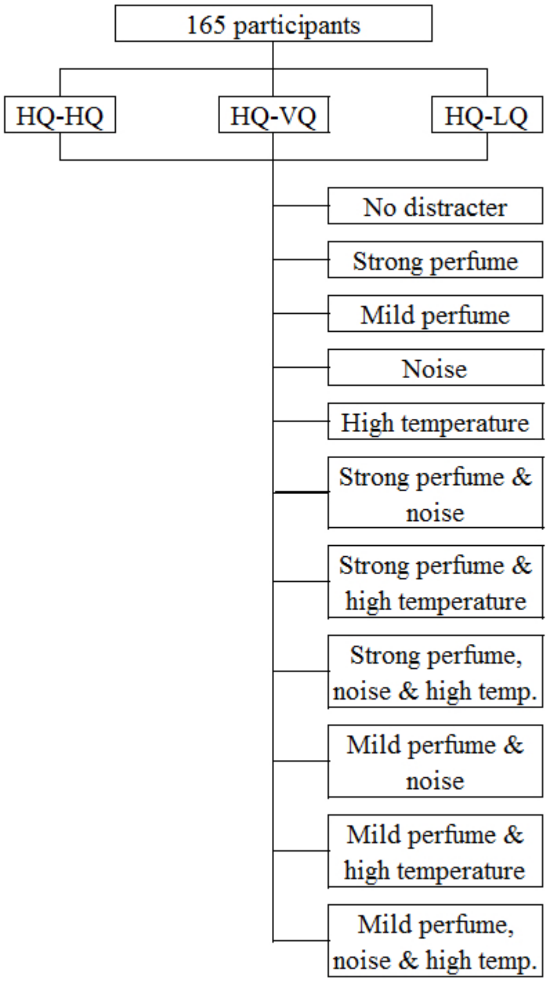

Figure 7.6: The conditions tested in Experiment 1.

as HQ since it was the threshold in the pilot study, i.e., the point above which the participants could not notice any difference in quality [177].

165 participants, of which 88 were female and 77 male with ages ranging from 16-40, from the undergraduate and postgraduate student population of the Sarajevo School of Science and Technology (SSST), volunteered for this study. None of the participants reported any problem with their sense of smell. All exhibited normal or corrected-to-normal vision.

Figure 7.7: Single frames (2, 110, 240) from the HQ animation used in the experiment.

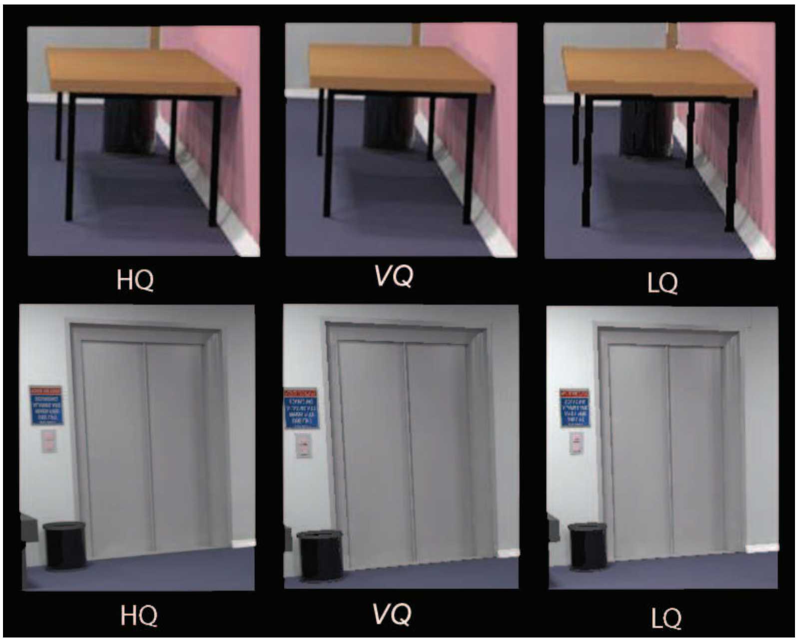

Figure 7.8: Close-up view of the differences between HQ, VQ and LQ images.

Each condition had 15 participants who were randomly divided into three equal groups and shown either a pair of animations rendered at high quality (HQ vs HQ), high and low quality (HQ vs LQ) or high and variable quality (HQ vs VQ). Participants were asked to identify which animation was of better quality from the pair of animations shown. They were also asked to point out where exactly they noticed the drop in quality, which object and which area. To determine this, frames were printed out from the animations and the participants were at that point allowed to play the animation a few more times to give a more precise answer (see Figure 7.9). However, they were not allowed to change their mind regarding the answer they had already provided, i.e. the animation they had chosen.

7.2.5.1 Results

The results of the experiment are shown in Figures 7.10, 7.11 and 7.12, while the summary of the results is given in Figure 7.13. The graphs show what percentage of participants chose which animation for each of the conditions. The difference between HQ and LQ animation was obvious to all participants and as expected the

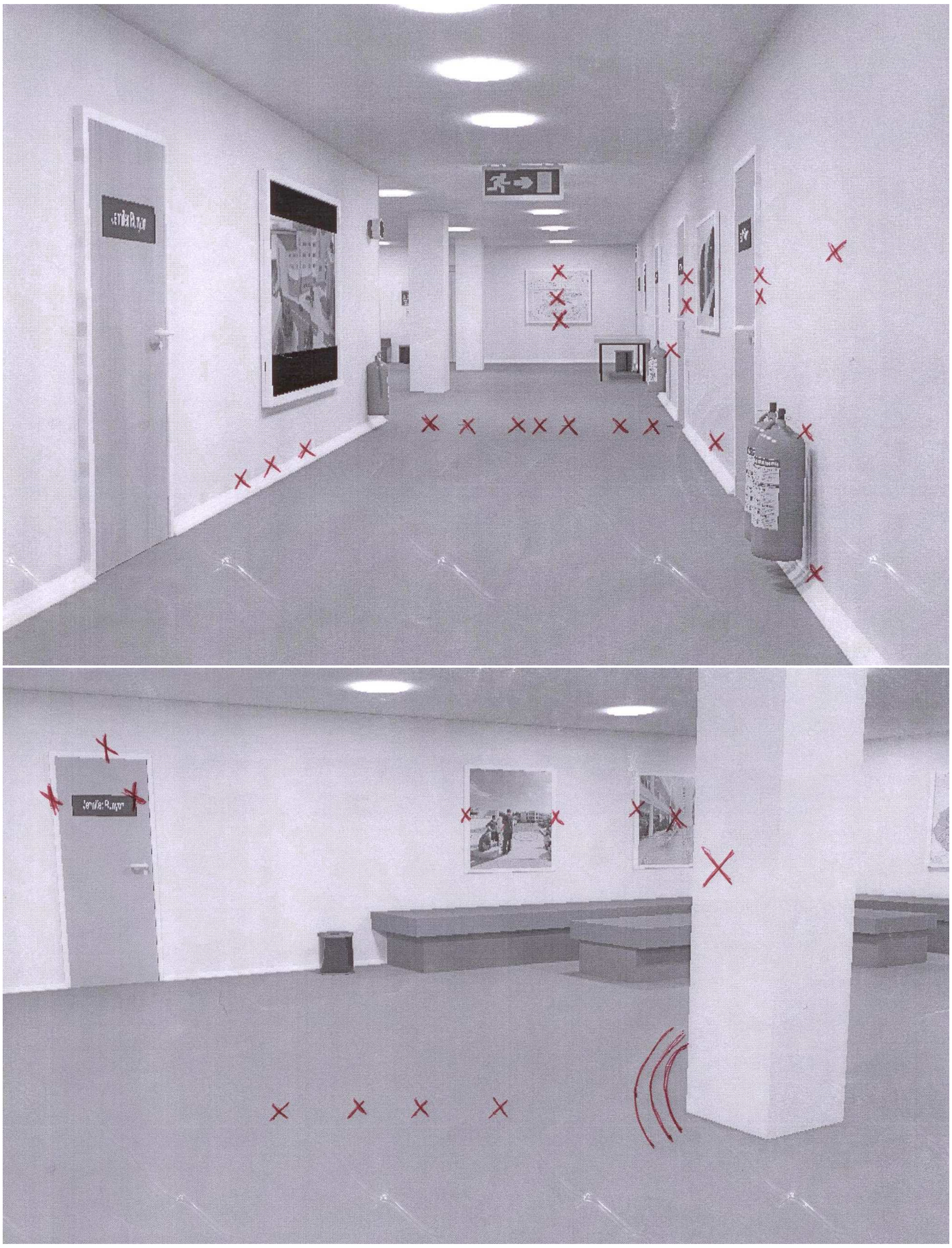

Figure 7.9: An example of the printed frames with users' responses of where they noticed the quality difference marked with red crosses.

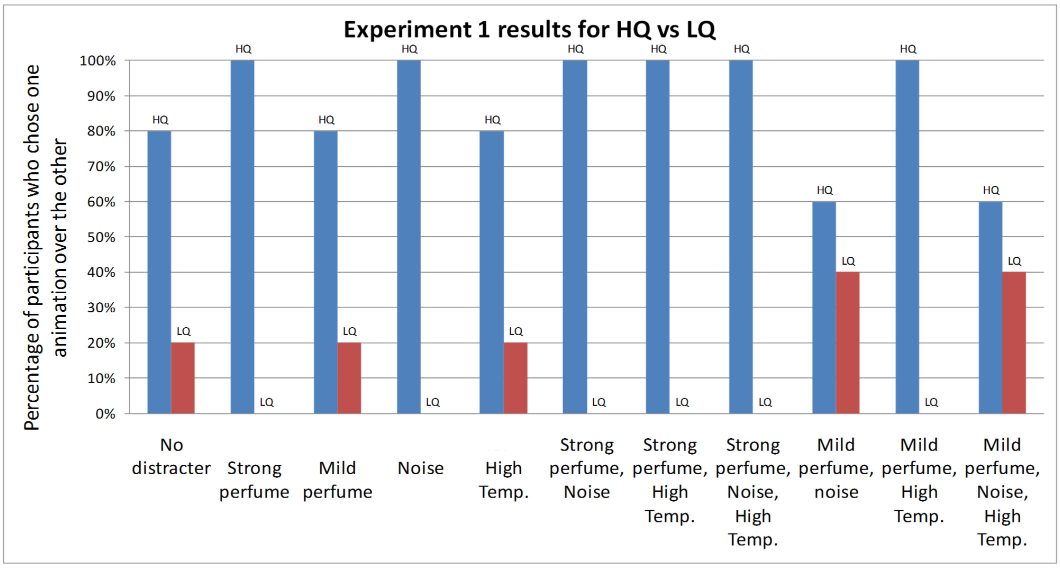

Figure 7.10: Results of Experiment 1 for HQ vs LQ.

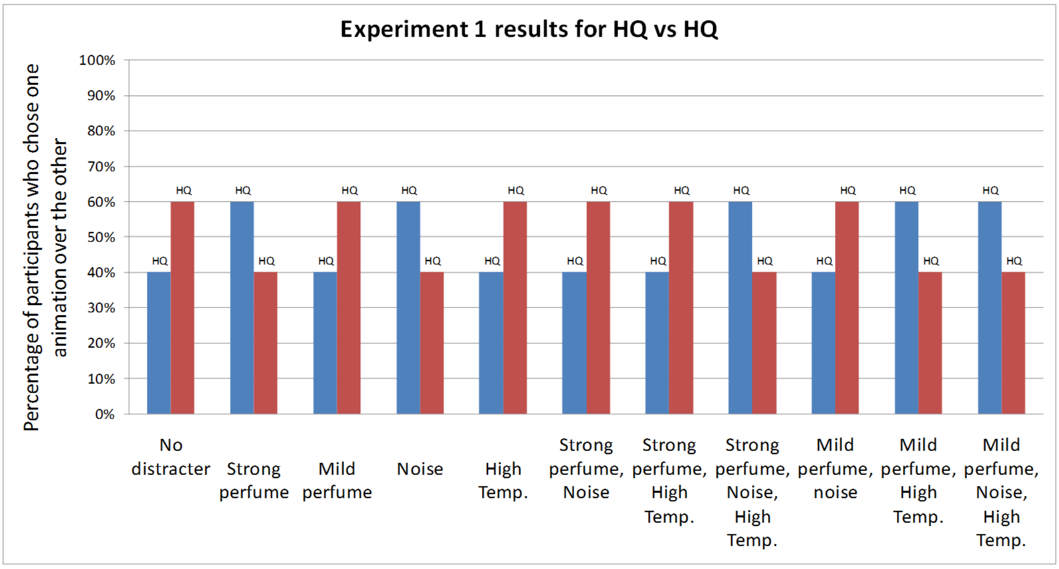

Figure 7.11: Results of Experiment 1 for HQ vs HQ.

participants could not determine the difference between the HQ-HQ pair of animations. The results indicate that with the VQ animation the influence of the other modalities had an impact.

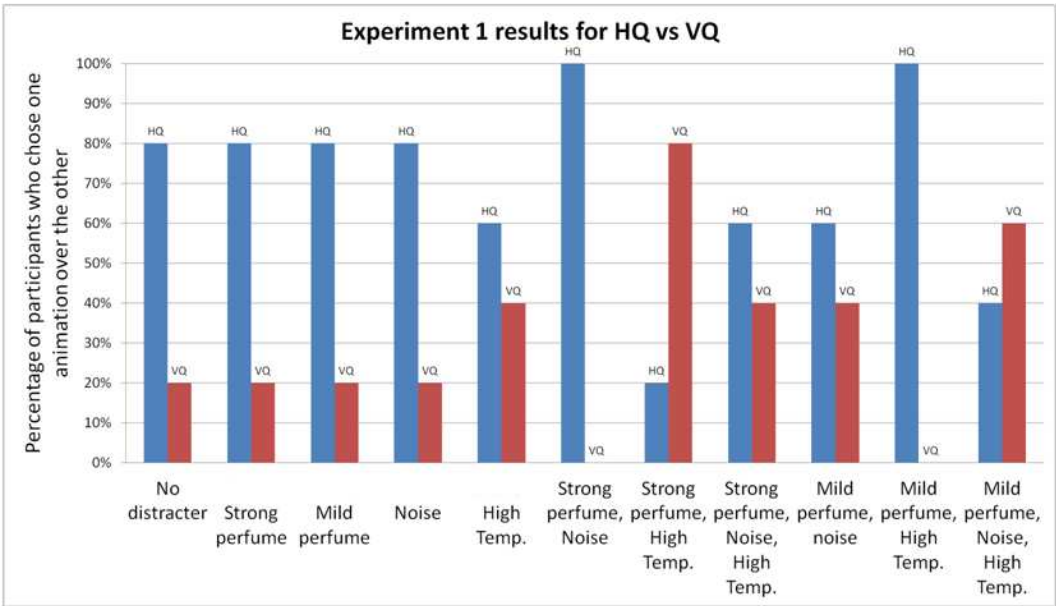

Figure 7.12: Results of Experiment 1 for HQ vs VQ.

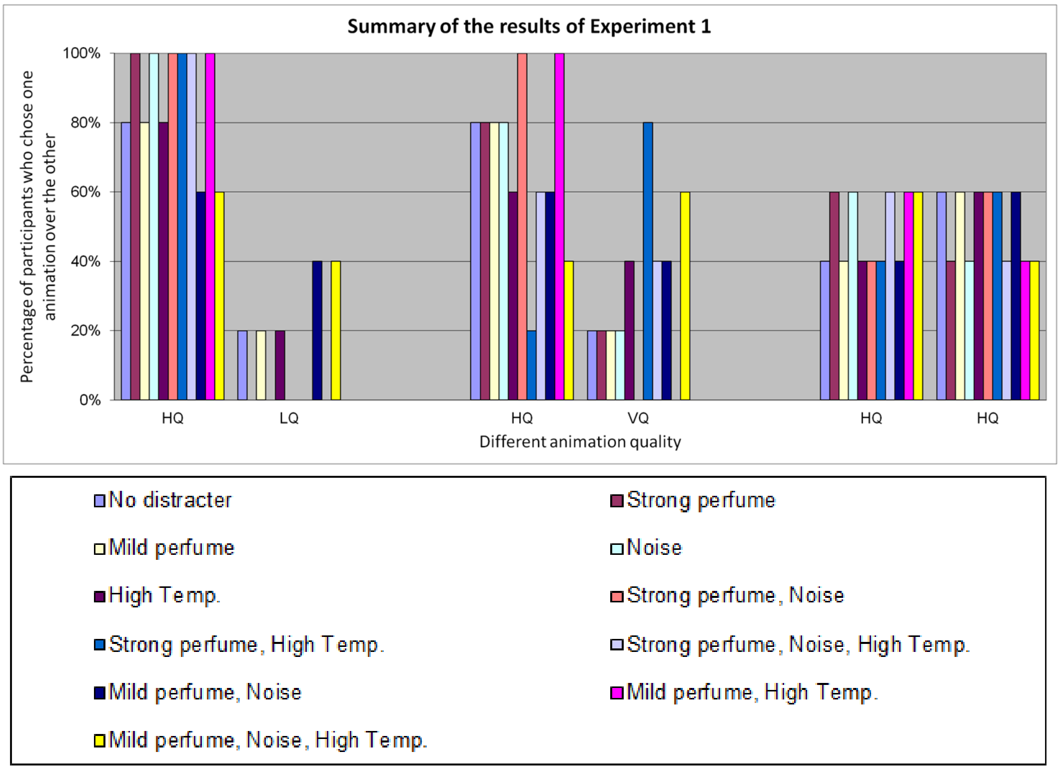

Figure 7.13: Summary of the results of Experiment 1.

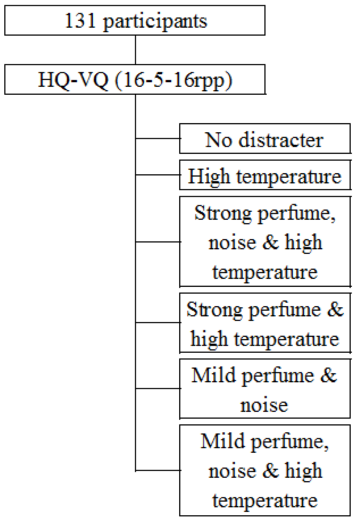

Figure 7.14: Conditions tested in Experiment 2.

It should be noted that we had only 5 participants per condition in this preliminary user study. The results of this initial study identified which conditions were promising for further investigation. Additional participants were then considered for these identified conditions.

7.2.6 Experiment 2

The second experiment tested only six conditions including a control group ("No distracter" condition). Five conditions were excluded from this further study due to either their probability values from the initial study (above 0.5: "Mild perfume"; "Strong perfume"; "Noise") or the fact that all the participants perceived the HQ animation correctly as the higher quality one ("Mild perfume and High temperature"; "Strong perfume and Noise"). The tested conditions for Experiment 2 are presented in Figure 7.14.

131 participants, of which 57 were male and 74 female with ages ranging from 16-25 of the student population at SSST volunteered for this study. All exhibited normal or corrected to normal vision and had no hearing or smell difficulties. Unlike the previous experiment, in this experiment participants were shown only two animations (HQ-VQ). The HQ-LQ pair of animations was excluded because the drop in

the quality was obvious to majority of participants.

Each condition had 25 participants. During a pilot study, it was decided to leave out the "Mild perfume and Noise" condition from further study as it was clear that participants were correctly able to perceive the HQ animation. We had 10 new participants for this condition and all of them were able to perceive a HQ animation as high quality one.

The VQ animation used in this experiment was different from the one used in Experiment 1. As mentioned in the description of Experiment 1, subjects were asked to point out where exactly they noticed the drop of quality in a shown pair of animations. The goal was to identify the threshold above which participants failed to notice the difference in animation quality in multi-sensory environments. The results showed that participants failed to see the difference in rendering quality above 5rpp. Therefore, the VQ animation used in Experiment 2 was rendered in a form of 16-5-16rpp (Figure 7.15). The beginning and the end of the animation were rendered at high quality while the inner frames (frames 11 to 230) were rendered by decrementing the ray quality from 16-5 and then back to 16 (see Figure 7.16).

7.2.6.1 Results

For the statistical analysis of the results, we used an unadjusted pair-wise t-test to determine between which pair of conditions significance occurred. The necessary calculations were done using the R software environment for statistical computing and graphics[1]. The results are shown in Figure 7.17 while the description of the labels used is given in Table 7.6.

From analyzing the *p-values*, it can be seen that 1 of the 10 differences appears significant (0.05), meeting the 95% confidence interval. This significance level was achieved between pairs 1 and 3 which represent "no distracter" and "strong smell, noise and high temperature" condition. There was no significance between any other pairs.

[1] http://www.r-project.org/

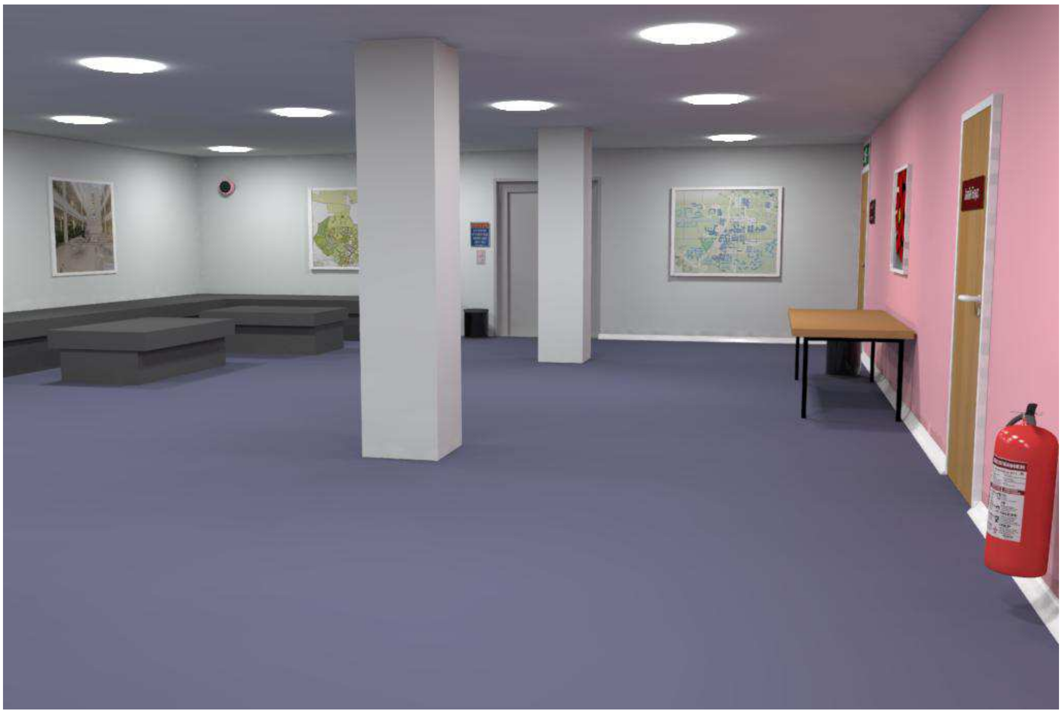

Figure 7.15: Frame 110 from VQ animation rendered in range from 16-5-16rpp.

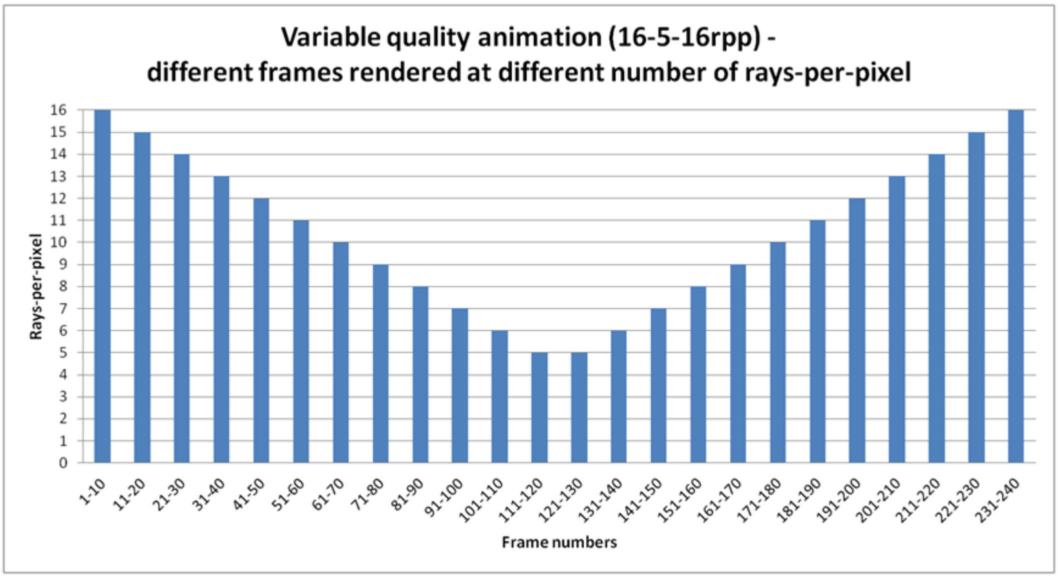

Figure 7.16: Different frames from the VQ animation rendered using different number of rays-per-pixel.

	1	2	3	4
2	0.57	-	-	-
3	0.05	0.16	-	-
4	0.26	0.57	0.40	-
5	0.26	0.57	0.40	1.00

p value adjustment method: none

Figure 7.17: Pairwise comparisons using t-test.

Table 7.6: Detailed description of labels used in Figure 7.17

label	description
1	No distracter
2	High temperature
3	Strong perfume, Noise, High temperature
4	Strong perfume, High temperature
5	Mild perfume, Noise, High temperature

The participants' responses are given in graphical form (see Figure 7.18) as well as in tabular form (see Table 7.7). The bar graph demonstrates that at the second condition that represents only one sense (high temperature), 60% of participants were able to see a quality difference. Moreover, the results show that if this single sense is added to another modality such as strong perfume or combination of mild perfume with noise, the percentage of 60% is reduced to 52%. Furthermore, if a combination of strong perfume and noise is added to high temperature, the percentage of participants who are able to perceive the HQ animation correctly, is substantially reduced: 40%.

7.2.7 Experiment 3

The final experiment is built on the results of Experiment 2. In Experiment 2, statistically significant results were achieved for the condition: "strong perfume, high

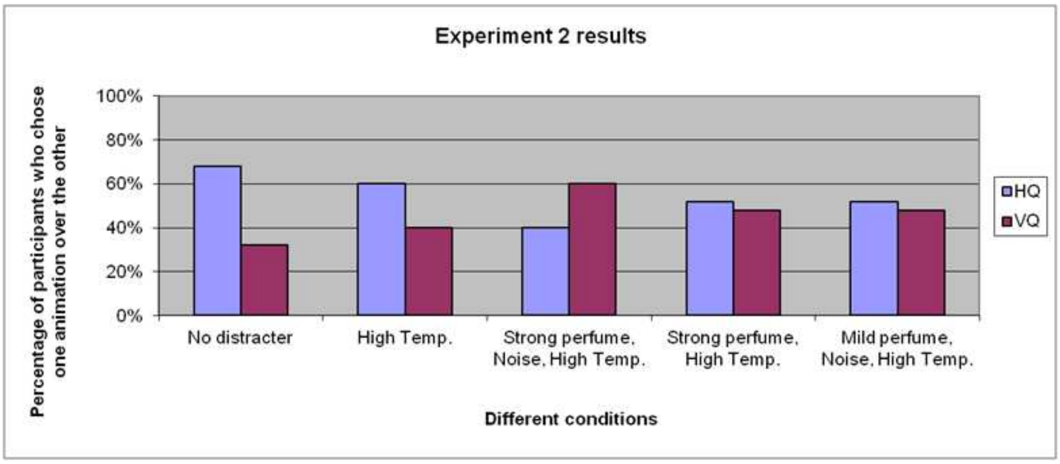

Figure 7.18: Results of Experiment 2 with the five conditions tested.

Table 7.7: Results of Experiment 2

Conditions	Rendering quality HQ	VQ
No distracter	17(68%)	8(32%)
High Temp.	15(60%)	10(40%)
Strong perfume,Noise,High Temp.	10(40%)	15(60%)
Strong perfume,High Temp.	13(52%)	12(48%)
Mild perfume,Noise,High Temp.	13(52%)	12(48%)

temperature and noise". This single condition was investigated further in Experiment 3 together with a "no distracter" condition which represents the control group (Figure 7.19). The goal of this final experiment was to see if parts of a scene could be rendered below 5 rays-per-pixel without the viewer being aware of the quality difference.

60 participants, of which 31 were female and 29 male with ages ranging from 16-40, from the undergraduate and postgraduate student population of the SSST, volunteered for this study. There were 30 participants per condition and all had normal or corrected-to-normal vision with no hearing or smell problems.

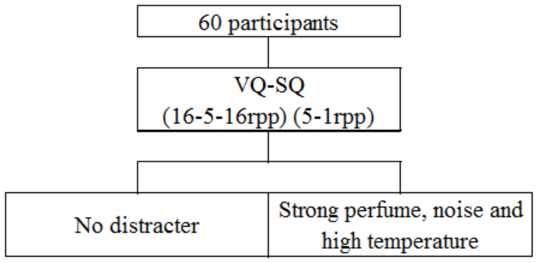

Figure 7.19: Conditions tested in Experiment 3.

In this experiment a VQ animation was rendered from 16-5-16rpp as in Experiment 2, and a new animation was created with the help of saliency maps. The most salient areas of the scene were rendered at 5rpp and non-salient areas at 1rpp (Figure 7.20). This method of rendering the animation was chosen rather than a naïve rendering of the animation with all pixels below 5rpp because all participants in Experiment 1 had noticed the drop in quality below 5rpp.

7.2.7.1 Results

The results from Experiment 3 are presented graphically (see Figure 7.21) and in tabular form (see Table 7.8). The results provide an interesting "mirror reflection". In the condition without any modalities ("no distracter") 63% of the participants were able to see the difference in animation quality and therefore correctly identify the higher-quality animation, while in the condition with "smell, sound and temperature", that percentage was decreased to 37%. For the purpose of statistical analysis a t-test was used to determine any statistical differences between the two samples. The level of significance according to the two samples t-test, calculated in the R software environment, is $p = 0.039$. This significance level means that these modalities influence visual perception and reduce a participant's ability to notice the difference in quality, allowing parts of a frame to be rendered below 5rpp, reducing computation time for each frame even further.

Figure 7.20: Top: Single frame (110) from SQ (5-1rpp) animation rendered using saliency maps. Bottom: Saliency map of the rendered frame from the animation.

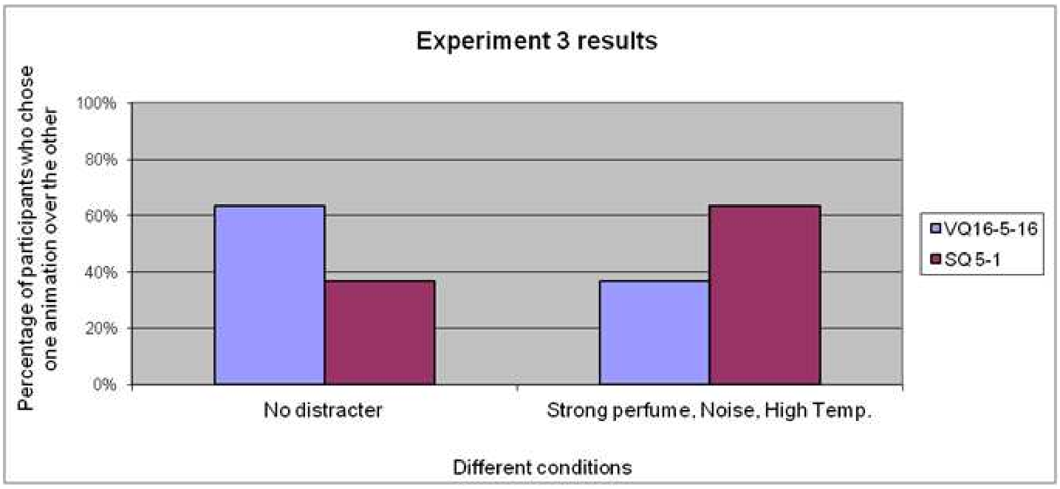

Figure 7.21: Results of Experiment 3.

Table 7.8: Tabular representation of Experiment 3 results

Conditions	Rendering quality	
	VQ(16-5-16rpp)	SQ(5-1rpp)
No distracter	19(63%)	11(37%)
Strong perfume,Noise,High Temp.	11(37%)	19(63%)

7.3 Summary

Producing a high-fidelity virtual environment requires simulating physically-based phenomena which entails substantially high computational costs. When faced with multiple sensory stimuli, humans are not able to maintain high precision in all of these simultaneously. This can be exploited in computer graphics, enabling only parts of a scene to be rendered in the highest quality without the viewer being aware of any quality difference. This selective rendering can significantly reduce overall computational costs without any loss in perceptual quality.

This chapter presented findings on how the presence of smell, sound and temperature can be used to influence the perception of the quality of an animation. Not only will the inclusion of these stimuli add to the perceptual realism of the virtual environment, but, as the results presented here show, they can result in major computational savings. The results further show that certain combinations of multi-sensory stimuli have greater impact on human visual perception than others. In particular strong combinations of all three tested stimuli have a more significant influence on perceived quality than the other combinations of stimuli which were tested.

In sense of numbers, we are talking about 78h 60min of saved time or approximately 10 working days (8h per day - 9.83 days). These numbers were acquired based on the rendering times for VQ (16-5-16rpp) animation. The time needed to render the second animation (5-1rpp) is approximately 13min per frame.

Even though one might think it would be hard to concentrate when having all these stimuli, this is nothing different from how we perceive the real world every day. We experience high temperatures at the beach or in a desert, and sounds and smells are very dependent on the environment in which we find ourselves. The significant computational times that are possible when producing multisensory environments could play a key role when considering such environments for training, eg. for soldiers deploying to Afghanistan, or for games such as virtual life.

Chapter 8

Discussion of Results and Findings

Throughout this thesis, we have presented findings on olfactory influence on the perception of computer generated image. Findings from other disciplines, such as psychology, on limitations of human visual system, have been exploited in order to maintain high quality perception but reduce the computed quality of whole image or its parts without this quality difference being perceived.

Even though multi-modal interaction has been a research topic ever since the introduction of Sensorama [70, 88], it has only recently been exploited in computer graphics. The most relevant findings on olfaction across all fields are presented in Table 8.1.

As can be seen, the main focus of previous research has been the introduction of smell (as it has been generally ignored by researchers due to lack of understanding on how it works, how is it processed in brain, existence of variety of smells, and so on) and testing its possibilities across different fields. Its implementation within computer graphics started with the development of olfactory displays. However, the results presented in Chapters 4 and 5 indicate that the significant potential lies in investigating the olfactory influence on perception. In these studies, exposure to smell (related and unrelated) decreased the perceived rendering quality threshold. Furthermore, in Chapter 6 we showed for how long we can exploit such an influence and whether a given task affects the participants' ability to perceive an odour in an

Topic	References
Learning and Memory	[37, 54, 60, 63, 67, 73, 74, 87, 115, 122, 153, 172, 181], Chapter 6
Olfactory cues in product judgment	[18, 76, 116, 161]
Olfactory Displays and E-Noses	[10, 40, 123–125, 143, 168, 184, 202–205, 211, 212]
Virtual Experience Enhancement	[46, 125, 183], Chapter 5
Computational Savings:	
Saliency Maps	Chapter 7
Selective Rendering	Chapter 4
Variable Quality	Chapter 6, Chapter 7
Olfactory Adaptation	Chapter 6
Sensory Interactions (Smell, Sound, Temperature)	Chapter 7

Table 8.1: Most relevant research on olfaction across different fields and main studies within computer graphics that inspired this work.

environment. Finally, introductory research was carried out on the multi-sensory influence on the perception of a virtual environment. In particular, the effect of smell, sound and temperature was investigated. It was shown that strong combinations of smell and temperature, together with noise, significantly affected the perception of a computer generated animation.

The main aim of this thesis was to investigate the effect of olfaction on perception in order to gain better insight and understanding of this relationship, making it then possible to reduce the computational costs without user noticing any difference in quality. This, in fact, was possible with the introduction of smell as an addition to the visual sense. This was investigated through conducting a series of psychophysical experiments (Chapters 4 - 7).

The investigation of olfactory influence on the perceived rendering quality (Chapter 4) showed that there exists a cross-modal interaction between these two modalities. Furthermore, this study showed that a smell-emitting object present in a virtual scene can be used to attract viewer's attention. This was confirmed by conducting a Chi-square analysis across smell conditions and scenes. This analysis compared the user preference between the images, rendered at different quality (HQ, LQ, SQ), presented with smell and without smell. Each participant was shown an HQ-HQ, HQ-LQ or HQ-SQ pair of images under one or the other smell condition. The results confirmed the main effects of Smell and Quality (χ^2=12.258, $p \leq 0.001$).

The study and results presented here indicate that with smell present in an environment we can render at HQ only the smell-emitting object, the bowl of flowers, while the rest of the scene can be rendered at significantly lower quality. This is in accordance with research findings presented in Chapter 2, which show that once our attention is captured by an event or an object, we fail to notice anything outside our viewing angle, even though it might be in our visual field [80, 167].

In the study presented in Chapter 4, participants connected the bowl of flowers with the omnipresent perfume smell from the real environment. It attracted their attention, and when asked which image they perceived as HQ, only 57% under "smell" condition was able to do so, compared to 80% under "no smell" condition. Applying these settings we were able to achieve a rendering time saving of 333% (HQ image - 50min; SQ image - 15min).

In the following study, presented in Chapter 5, we investigated whether similar findings could be achieved when applying the results in a game or computer generated movie. Two computer generated grass terrain animations were used in the study. Grass terrain represents the most common element of such environments as it can be found in almost all sport games such as football, tennis, cricket and so on.

Selective rendering using a level-of-detail approach was used for the rendering of the animations. As seen in section 3.5, it represents another way selective rendering can be used. In this study, the entire scene was rendered in HQ or LQ where the former was rendered with anti-aliasing and shadows while latter without anti-aliasing and without shadows. We used the same approach to rendering as Boulanger [20]. Furthermore, we used a related smell, the smell of freshly cut grass, and had two conditions, with and without smell.

Under the presence of related smell, 50% of participants were able to correctly identify HQ as HQ while under "no smell" condition, 80% were able to do so. The results were analyzed using Chi-square test and confirmed the main effects of Smell and Quality (χ^2=5.934, p=0.01). These findings mean we are able to deliver a LQ animation computed one-and-half times faster than the HQ version without any perceptual difference to the viewer. As reported by many other researchers (section 3.5: [46,125,183]), smell does enhance the virtual experience. This was also the case with our participants who in a post-experiment oral discussion reported enjoying the olfactory experience in a combination with computer generated scenery.

Although the goal of the experiment presented in Chapter 5 was not to test the memory of our participants, the possible degradation of memory due to the presence of smell cannot be discounted as the animations, although randomised, were not shown simultaneously. Therefore, it would be necessary to investigate this further in future work by showing the different quality animations side-by-side which should reveal whether smell is indeed degrading memory and thus contributing to the failure of the participants to notice the quality differences.

Having identified that smell (related or unrelated) does indeed attract viewers attention allowing us to use selective rendering and therefore achieve significant computational savings, we needed to determine the amount of time for which such exploitation can occur for. We thus investigated the adaptation time period and what happens once a participant does get adapted to smell. This was the study presented in Chapter 6.

For this study computer generated animations of a corridor walk-through were created. One version was rendered in HQ (16rpp - threshold above which no perceptual difference is found according to preliminary study results presented in Chapter 7 and work done by Mastoropoulou et al. [112]), and another one in VQ (variable quality) where after equal number of frames (180), the quality of the rendering, in terms of the rays-per-pixel was lowered (16-15-14-...-1rpp). Initially, only two conditions, "smell" and "no smell" were considered. The smell of lemon was chosen as this is a common household smell and therefore familiar to all participants.

Participants were shown first the HQ animation, and then the VQ one. They were asked to stop the second animation once they noticed the difference compared to the first one. For the "smell" condition, they were asked to hold a piece of paper impregnated with the smell under their nose throughout watching both animations. The average time it took for a participant to notice the quality difference was 3min 19sec (199 seconds). A third condition was then considered, where participants were asked to hold the smelly paper for this same amount of time (199 seconds) and only then were they played both animations with same instructions. 100% of participants noticed the difference between 16rpp and 8rpp under "no smell" condition, whereas 92% noticed the difference under the third condition ("smell present before the start and throughout animations"). This almost identical result suggests that the smell adaptation indeed happens sometime after 150 seconds. Although, holding a smelly paper under a nose might be considered as a distraction, holding a smelly paper is not difficult and no different from, for example holding a mouse or a joystick.

Once the adaptation time period had been identified, further investigation was carried out in order to identify the influence that smell may have on the performance on a given task (Chapter 6). This study was done to help identify whether participants' performance will be increased or decreased and to what extent smell exploitation can be applied in computer graphics when participants are faced with a task such as finding a target in a game or missing element in a puzzle. The motivation for this study partially lies in the results presented by [18, 76, 116, 161] where they reported that smell affects product judgment meaning that more sales can be made in a shop containing a smell as opposed to non-odorised shop.

In this study, participants were given the relatively simple task of counting the number of large blue balls in an image. The number of balls in the image remained constant across all time slots and conditions. The results show that participants generally perform better in the presence of smell. The difference in performance varies from 1% to 35% between "smell" and "no smell" condition. Similar conclusions can thus be drawn from our results as those from the previous research, as they show that in the presence of smell participants tend to be more focussed and eager to complete the given task.

Taking into account the adaptation time period, we may conclude that once adapted to smell participants tend to perform similarly under the "smell" and "no smell" conditions as the difference in performance is only 8%. A similar conclusion can be drawn from the first study presented in Chapter 6 where participants performed almost the same in the "no smell" and "smell before the start and throughout animations" conditions. Only two time slots were outliers to these conclusions, the first - 15sec - and the last - 300sec time slot. This might be related to task complexity. 15sec represents very little time to undertake the task, while with 300sec participants had perhaps too much time to complete a task and thus started to recount. Future work would need to investigate this further.

Furthermore, the same study (Chapter 6) also investigated whether smell will be noticed when entering and when leaving the experimental environment. We wanted to investigate whether the presence of smell may have an inattentional blindness effect (when given a task, participants fail to notice the surrounding). Figures 6.13 and 6.14 show that participants noticed the smell when they entered, but seemed to ignore it when leaving (reported "no" or "don't remember" in majority of cases). Here, only the 15sec time slot is considered as an outlier since majority of participants did not remember smell being there when entering the environment. This once again can be attributed to the very little time given to participants and their lack of ability to comprehend what is happening (ie. enter the room, perform a task, leave a room, and fill the questionnaire).

Finally, in the last study (Chapter 7) we investigated whether the rendering threshold could be even further reduced in the presence of other modalities such as sound and temperature. Before combining these modalities together, we first tested individual senses. In the case of smell, the results revealed that a strong smell had more effect on the perceived rendering quality than a mild smell. For completeness purpose we decided to also test a mild condition. High temperature and noise were chosen in the same manner as strong smell was (studies done by colleagues Sadžak and Hulusić, respectively).

Three experiments (with combinations of strong and mild smell, sound and temperature sensory stimuli) were conducted. However, with each new experiment we reduced the number of different conditions, animation pairs and number of rpp used across all animations. The results of Experiment 1 revealed that participants could not see the difference between animations rendered in same quality (i.e. HQ-HQ) or HQ-LQ, and no perceivable difference was found above 5rpp. To adequately investigate the large number of conditions in the first experiment (three animation pairs, eight conditions) would have required a large number of participants. This first experiment was thus treated as a pilot experiment for the next experiment (Experiment 2). In Experiment 2 six conditions were tested. Each participant was shown one pair of animations, one rendered in HQ and another one rendered in VQ (16-5-16rpp). The new animation (VQ) was created to verify the findings from Experiment 1 (5rpp threshold) by increasing the number of participants and decreasing the number of conditions. The results were analyzed using a pair-wise t-test across the different conditions and revealed a significant effect between Strong smell, Noise and High temperature. This particular combination of stimuli was tested further in Experiment 3, where we investigated if the perceived rendering threshold could be even lower, ie. below 5rpp. 63% of the participants were able to identify HQ as HQ while in the presence of modalities (strong smell, noise, high temperature) only 37% did so. Interestingly, we have a mirror reflection of the results between these two conditions. The multi-modal effect found in the second and third experiments indicates that it would be possible to achieve significant speedup in rendering (up to 78.60 hours) when smell, noise and temperature are all present in a virtual environment.

In summary, the knowledge gained from all the studies can be used to manipulate a rendering system, saving computation while maintaining the same perceptual experience as if the entire animation had been rendered in high quality. Such savings could make it possible to render complex high-quality animations without the need for large computational resources, such as a render farm. This is very timely as the games, movie, and simulation industries are continuing to demand high-fidelity graphics, more complex virtual environments, a high level of interactivity and inclusion of different modalities.

Chapter 9

Conclusions and Future Work

Visual perception is becoming increasingly important in computer graphics. Research on human visual perception has led to the development of perception driven computer graphics techniques, where knowledge of the human visual system and, in particular, its weaknesses are exploited when rendering and displaying 3D graphics.

However, a human's perception of an environment is not only through what we see, but is also significantly influenced by our other sensory inputs, including sound, smell, touch and even taste. The presence of one or more additional senses may dramatically alter the way we view the scene with our eyes. Furthermore, the presence of many sensory stimuli, including smell, may influence the amount of cognitive resources available to a viewer to perform a visual task.

Achieving a high-fidelity virtual environment requires huge computational costs. Therefore, in order to reduce this computational effort when creating such environments, designers can take into account other factors, such as the influence of different singular and multi-sensory modalities on the Human Visual System.

The main goal of the research presented in this thesis has been to aid the development of such high-fidelity virtual environments by taking the advantage of the olfactory influence on the perception of an object quality. More specifically, we investigated if smell and its combination with other modalities such as temperature and sound, could affect the way we perceive the environment around us and therefore enable a reduction in the overall computational costs without any loss in perceptual quality.

This chapter summarizes the contributions we have made throughout this study and discusses ideas for the future work.

9.1 Thesis Contribution

In this thesis, a detailed overview of the olfactory-visual cross-modal and olfactory-sound-temperature multi-modal interaction has been given. This includes the main findings across different fields, especially focussing on the work carried out within computer graphics (Chapters 2 and 3). The novel work, presented in Chapters 4, 5, 6 and 7 builds on these findings. Through a series of psychophysical experiments we investigated the effect olfaction has on a human visual perception and how it can be utilized to benefit computer animation developers.

The work undertaken in this thesis has clearly shown:

- Cross-modal interaction between olfaction and vision does indeed exist (Chapters 4, 5, 6 and 7). This work was published in [33, 144, 146].

- Smell emitting objects do attract human visual perception. This allows us to selectively render in HQ (16rpp) only the smell emitting object while the rest of the scene can be rendered at significantly lower quality (9rpp), without the viewer being aware of this quality difference. This selective rendering enables a computation speed-up of 333% to be achieved (Chapter 4). This work was published in [144].

- Related smell can be used to reduce the quality of displayed animation without perceptual difference to the user. This allows the entire animation to be rendered one-and-half times faster, a significant computational saving (Chapter 5). This work was published in [146].

- Our results show that for our experiment, adaptation to smell does indeed affect participants' ability to determine quality difference in the animations. After exposure to the smell before undertaking the experiment, participants were able to determine the quality in a similar fashion to the "no smell" condition. The results suggest that adaption to smell in our experiment happens sometime after 150 seconds. Since no similar study has been done before, this information serves as an important indicator on the amount of time smell may be exploited in a virtual environment for the purpose of reducing computational costs without affecting the user's experience within the environment (Chapter 6). Future work should attempt to determine the adaptation time for a variety of smells more accurately.

- Smell increases the performance on a given task (Chapter 6). Under the influence of smell, participants tend to perform up to 35% better as opposed to the group of participants who were not under the smell influence. Therefore, this fact can be exploited in for example educational and training type of virtual environments, as participants can comprehend and implement given tasks in shorter periods of time.

- The perceived rendering threshold can be decreased with the introduction of sound and temperature, as addition to smell and vision (from 16rpp to 5rpp - achieved savings for a single frame of 30min 37sec) (Chapter 7). This work was partly published in [33].

- The rendering threshold can be decreased even further with the introduction of saliency maps rather than variable quality rendering. For an animation rendered in 16-5-16rpp to one rendered in 5-1rpp the time saved equated to approximately 10 working days for a 10sec animation (Chapter 7).

The novel findings regarding the perception of computer generated images and animations under the influence of olfactory stimuli can be used in the development of various computer generated environments such as 3D games, and virtual cities.

The computational savings are significant and thus could be exploited in the development of interactive, highly complex and demanding environments for various purposes such as virtual therapy, training, education.

In addition, our work shows the potential of smell inclusion for significantly enhancing the participant's experience in the virtual environment (Chapter 5). This does highlight the need for developing the necessary hardware (such as delivery and smell evacuation systems, GPUs, etc) which is currently one of the main limitations. In the past this was due to the lack of knowledge about for example, olfaction, how we smell, and the large number of smells a human can identify. The work presented in this thesis has shown that, even with the current limited knowledge of olfaction, it is still possible to introduce and indeed exploit smell in virtual environments to render perceptually high-quality environments selectively at a significantly reduced computational cost. Care needs to be taken though, about smell adaptation and consideration should be given to how participants may perform on a task once adapted to the smell.

Since this is the first study in computer graphics that investigates this phenomenon, more work is needed in order to develop a framework that could build on the findings from this thesis. This thesis thus provides a foundation from which future work can proceed, with results showing the potential of olfactory use in virtual environments.

9.2 Future Work

This work has opened up many new avenues of research and identified areas where further work is required to be able to draw more substantial conclusions. Future work will investigate far more different and complex smells, for example (pleasant vs. unpleasant, higher vs. lower concentrations) and their effects on perception. This will of course be affected by the user's own sense of smell (personal like and dislike), as well as cultural background which must be taken into account [8, 120, 171, 201]. Eye-tracking will also be used to investigate how the viewer's eye gaze is affected by the presence of a scent in general as well as in the presence of different smells. Will an unpleasant smell make a person turn his/her head and therefore miss a detail on a screen or will it make them more focussed on a given task, whether it is observing the quality, counting the balls, etc?

The impact of smell on memory also needs to be explored in more detail. Showing the animations side-by-side (rather than one after the other) should shed more light on the possible effects of memory in remembering image quality with and without the presence of smell.

Future work needs to also address the limitations of smell such as the difficulty of mixing and then evacuating smells from the air. We are always surrounded by a variety of different smells, and not just one at the time. Achieving high-fidelity virtual environment would require the mixture of different smells. Therefore, in order to exploit the findings from this thesis, the effects of smell in an animation needs to be considered once the smell emitting object has disappeared from the view.

Another issue that has been tackled in this thesis is the adaptation time period. However, more detailed research is needed in order to understand what happens once a user gets adapted to a smell and more precisely when this adaptation occurs. Will the addition of a new smell allow us to continue the exploitation of a human visual system or will it serve as a distraction? Whether participants would notice such a smell or not could be (depending on the results) further exploited. Such research may require fMRI data in order to record brain activities as they consciously might not recall the new smell but unconsciously, it may be recognized.

Furthermore, we will look at categorizing smells into "quick", "medium" and "slow" to detect. In addition, a simple test will be developed to help understand each user's perception of the smells being considered in any virtual environment. Attention will be paid to the participant's age, smoking habits and gender. The test will also examine the participant's perception of a smell based on familiarity (familiar/unfamiliar) and hedonism (pleasant/unpleasant). These inputs will then be used to weigh the "arrival" time of a smell at each cell into a more authentic "perception" time.

Finally, future work will also investigate which of the senses, considered in Chapter 7, is the dominant one i.e. smell, sound or temperature and thus what the likely impact will be for the perceived visual quality of our selective renderer as a viewer becomes adapted not just to smell, but to all these senses. Moreover, can these modalities be used in a virtual environment once the SEO is removed and what outcomes will such an inclusion produce?

Beside the research on olfaction and its perception, the findings presented in Chapter 4 do indicate a noticeable difference in perception by those familiar with computer graphics and those who are not. This suggests that multi-modal virtual applications (for example games and virtual cities) may need to be selective rendered at different qualities for each group. More computational savings should be possible for those unfamiliar with computer graphics, compared with those who are familiar. Future work should explore the quality boundary between these two communities more thoroughly to help quantify the difference in computational savings that may be possible.

Finally adding smell to an interactive computer graphics scenario is a key long term goal of the research undertaken in this thesis. However, such a real-time rendering system will require a large number of different aspects to be tackled, including development of the software and hardware infrastructure. Achievement of such a high-fidelity multi-modal interactive virtual environment would benefit not only virtual worlds but also the game and advertising industries, archaeology and perhaps, even the movie industry.

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Appendix A

Consent form used in all experiments

Consent form

I have been asked to participate in an experiment that investigates an area of computer graphics. I give my free consent by signing this form.

- I have been informed about the research and why it is taking place.
- I understand that my participation in this research is voluntary.
- I understand that I can withdraw from the research at any time.
- I understand that my data will be anonymous.
- I understand that I will be provided with a debrief after taking part in the experiment.

Signature __________________________

Date ______________________________

Appendix B

Experiment on olfactory influence on perception

Questionnaire

Age ______

Gender ___________

Nationality ___________________________

Do you have normal or corrected to normal vision? _______

Do you have any problems with sense of smell such as cold or allergy? ________

How many hours per week, on average, do you play computer games? (if at all) _______

Have you ever attended any courses on Computer Graphics? _______

Appendix C

Experiment on smell adaptation

Questionnaire

Age ______

Gender ___________

Nationality ___________________________

Do you have normal or corrected to normal vision? _______

Do you have any problems with sense of smell such as cold or allergy? ________

How many hours per week, on average, do you play computer games? (if at all) _______

Have you ever attended any courses on Computer Graphics? _______

Please write down the time when you noticed the difference: ___________

Please explain where exactly you saw the difference:

Appendix D

Experiment on task performance in the presence of smell

Questionnaire

Age ______

Gender ___________

Nationality ___________________________

Do you have normal or corrected to normal vision? _______

Do you have any problems with sense of smell such as cold or allergy? ________

How many hours per week, on average, do you play computer games? (if at all) _______

Have you ever attended any courses on Computer Graphics? _______

How many large blue balls were there in an image? _________

Did you notice any smell when you entered the room? Yes No Don't remember
If yes, could you please name the smell? _____________________

Did you notice any smell when you left the room? Yes No Don't remember
If yes, could you please name the smell? _____________________